A MODEL STUDY OF THE HYDRAULICS RELATED TO FISH PASSAGE THROUGH EMBEDDED CULVERTS

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in the
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by

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ABSTRACT

This aim of this research program was to provide a better understanding of the hydraulics of embedded culverts. The results of this research may provide support to improving the methods of culvert installation with respect to fish passage requirements. The overall objective of the research program was to quantify the hydraulic conditions, which included flow depths and velocity distributions, for at-grade and embedded culverts.

A physical hydraulic model study was conducted in the Hydrotechnical Laboratory of the Department of Civil and Geological Engineering at the University of Saskatchewan. A culvert with a length of 8 m and a diameter of 500 mm was studied. The culvert slope was set at approximately 0.75% for all tests. The tests consisted of a culvert that did not have backfill material or baffle structures placed within the barrel. Only part-full flow conditions were studied. The hydraulic conditions in the model culvert barrel were altered by using three invert placement configurations (at grade, 0.1*D* and 0.2*D*) and three discharges (50 L/s, 70 L/s, and 90 L/s) resulting in nine combinations of culvert invert placement and discharge. For each combination of placement and discharge, the following data were collected along the length of the culvert:

- Velocity distributions within a cross-section of the flow at five locations;
- Vertical velocity profiles along the centerline of the culvert at 10 locations; and
- Flow depths along the centerline of the culvert at 17 locations.

From the results of the study, an embedded culvert has lower velocities than an at-grade culvert provided that the culvert diameter, culvert slope and discharge are the same. On the basis of the work done in this study, the mean velocity of the flow field decreased by approximately 15% when embedding the culvert 0.1*D* and 30% when embedding the culvert 0.2*D*. When the culvert was placed at grade, on average approximately 44% of the flow area was less than the mean velocity of the flow. When the culvert was placed at an embedment of 0.1*D* and 0.2*D*, on average approximately 70% and 98% of the flow field had a velocity less than the mean velocity of the flow corresponding to the at-grade conditions.

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LIST OF SYMBOLS

A	flow area (m^2)
A_r	ratio of the cross-sectional area of the culvert to that of the downstream channel
D	culvert diameter (m)
g	acceleration of gravity (m/s^2)
h_W	headwater depth (m)
H	differential head or total head loss given by $H_e + H_f + H_o$ (m)
H_e	entrance head loss (m)
H_f	friction head loss (m)
H_o	outlet head loss (m)
H_R	head recovery (m)
k	boundary roughness height (m)
k_e	entrance loss coefficient
k_s	Nikuradse equivalent sand grain roughness height (m)
L	length of culvert (m)
n	measure of boundary resistance referred to as Manning's n
Q	discharge (m^3/s)
R_h	hydraulic radius (m)
R_x	Reynolds number using streamwise distance as the characteristic length [Ux/υ]
RMS	Root mean square
$RMS_{u'}$	RMS of the velocity fluctuations in the x-direction (m/s)
$RMS_{v'}$	RMS of the velocity fluctuations in the y-direction (m/s)
$RMS_{w'}$	RMS of the velocity fluctuations in the z-direction (m/s)
S	slope of the energy grade line
t_w	tailwater depth (m)
$TI_{u,}$	turbulence intensity in the x- direction
TI_v	turbulence intensity in the y- direction
TI_w	turbulence intensity in the z- direction
U	free stream velocity (m/s)
u	x-direction (i.e. streamwise) velocity (m/s) at z
$\overline{u}$	time-averaged velocity in the x-direction (m/s)

u_*	shear velocity found by $\sqrt{gR_hS}$ (m/s)
u_{*o}	shear velocity at the central axis (m/s)
Δu_m	max deviation in velocity from Equation 2.2 in the upper region of the flow (m/s)
$\overline{v}$	time-averaged velocity in the *y*-direction (m/s)
V	mean velocity of the flow found by Q/A (m/s)
V_1	approach mean velocity (m/s)
V_2	downstream mean velocity in the channel (m/s)
V_b	mean velocity in the culvert barrel (m/s)
V_n	mean velocity of the flow during normal flow conditions (m/s)
$\overline{w}$	time-averaged velocity in the *z*-direction (m/s)
y	distance from the central axis of flow (m)
x	distance from the culvert inlet (m)
x_s	distance from the spillway inlet (m)
y_b	depth of water in the culvert barrel at the culvert outlet (m)
y_o	half the top width of flow (m)
z	vertical distance above the bed (m)
z_d	height above culvert invert were velocity profiles deviate from Equation 2.2 (m)
z_o	constant (m) related to the bed roughness element size
z_y	height above the datum at a non-central plane (m)
Z_y	average depth of flow at a non-central plane in the uniform flow region (m)
δ	boundary layer thickness (m)
θ	angle of ADV probe as given by the ADV traverse system (deg)
τ_o	bed shear stress at relative distance y/y_o (N/m²)
τ_∞	bed shear stress at the central axis (N/m²)
υ	kinematic viscosity of the fluid (m²/s)

CHAPTER 1

INTRODUCTION

1.1 Background

In Western Canada, there are a large number of roadway stream crossings, and culverts are the most popular stream crossing structure because of their lower comparable cost relative to other alternatives (Katopodis 1992). In the past, culvert design focused primarily on the size of culvert required to pass a large discharge event of a given exceedance probability (Klingeman 2000 as cited by Gregory et al. 2004). However, with the growing concern of adverse impacts on aquatic environments and legislation such as the Fisheries Act (R.S., 1985, c. F-14), culverts must now be designed to satisfy two objectives: (1) to safely convey water from one side of a roadway embankment to the other, and (2) to maintain successful movement of fish within the stream.

In Canada, the legislated requirements for fish passage and culvert installations are outlined in sections 20 and 35 of the Fisheries Act (R.S., 1985, c. F-14):

> "20. (1) Every obstruction across or in any stream where the Minister determines it to be necessary for the public interest that a fish-pass should exist shall be provided by the owner or occupier with a durable and efficient fish-way or canal around the obstruction, which shall be maintained in a good and effective condition by the owner or occupier, in such place and of such form and capacity as will in the opinion of the Minister satisfactorily permit the free passage of fish through it."

> "35. (1) No person shall carry on work or undertaking that results in the harmful alteration, disruption or destruction of fish habitat."

The term ‘free passage of fish’ used in subsection 20(1) is quite general and depends mainly on the species of fish. For example, fish swimming capabilities vary considerably among species, and a delay period of less than three days in annual spawning migrations is usually accepted by regulatory agencies for several freshwater species, while no migration delay is acceptable for Pacific salmon (Katopodis 1992). Therefore, subsection 20(1) of the Fisheries Act is generally interpreted such that a fish passage delay should not exceed three days more than once every 10 years and that the mean cross-sectional velocity in a culvert should not be greater than the capability of the weakest swimming fish (Katopodis 1992; Saskatchewan Environment 1995; Alberta Transportation 2001).

Standard culvert designs rarely meet fish passage criteria because culverts concentrate the flow which causes higher velocities than would occur in a natural channel. Therefore, there are several methods for modifying a standard culvert design to satisfy fish passage requirements. These methods are typically divided into two categories: stream simulation design and hydraulic design. Stream simulation design focuses on sizing and installing culverts to avoid constricting the stream or river channel. Stream simulation culverts are designed to maintain existing channel conditions such as slope, flow depth and velocities, and bottom substrates (House et al. 2005). This is the preferred culvert design method for accommodating aquatic organisms in a stream (DFO 2005); however, this method is very costly due to the large-sized structures and possibly strong foundations required.

Hydraulic design focuses on flow depths and velocities that avoid adverse conditions within a culvert for the design fish species. These design methods include increasing the culvert size, embedding the culvert invert, or installing baffles (Alberta Transportation 2001). A common hydraulic design method is a combination of the three, such that a large diameter culvert is embedded below the stream bed elevation, and then rock material or baffles are placed along the culvert invert (Alberta Transportation 2001). Adding suitable substrate material to the invert of an embedded culvert increases the roughness of a culvert bottom and reduces water velocities (Alberta Transportation

2001). Baffles are used to provide hydraulic obstructions at regular intervals that dissipate energy, increase overall effective roughness, create turbulent flow, and provide potential resting zones for fish (Alberta Transportation 2001). Baffles are economical for remedying existing culverts; however, they create an artificial environment, reduce culvert conveyance capacity, and require frequent maintenance and routine inspection (Alberta Transportation 2001).

If a culvert is embedded below the stream bed elevation and is not backfilled with substrate, then the flow area for a given discharge is increased and the mean velocity of the flow is decreased, provided that the culvert is flowing only partially full. From this concept, it is thought that, for a given size of culvert, an embedded culvert will meet a fish passage mean velocity criterion when a culvert installed at grade might not.

A velocity distribution exists within a culvert barrel flowing partially full due to the presence of a free surface and to the friction along the wall (Chow 1959). Recently it has been recognized that the lower velocities near the bed and walls may provide adequate conditions for fish passage especially since it has been shown that fish have a natural ability to find the low velocity zones (Behlke et al. 1991; Lang et al. 2004). Thus, there is question as to whether the mean velocity is an appropriate criterion for assessing a fish's ability to swim through a culvert. Quantifying the velocity distribution within a culvert may lead to less conservative fish passage design criteria, which will lead to less costly culvert installations.

The focus of the work reported herein is to show how embedding a culvert may help improve fish passage abilities compared to culverts placed at grade. Also, this research study addresses the velocity distribution issue in the context of culverts placed at grade or embedded below the stream bed grade level.

1.2 Objectives of the Research

The aim of this research program was to provide for a better understanding of the hydraulics of embedded culverts. The results of this research may provide support to improving the methods of culvert installation with respect to fish passage requirements. The overall objective of the research program is to quantify the hydraulic conditions, which include flow depths and velocity distributions, for at-grade and embedded culverts. Specifically, the objectives of the study are:

- To quantify the velocity distribution found within a culvert placed:
    - at grade with uniform flow conditions throughout the length of the culvert;
    - at an embedment depth of 0.1 times the culvert diameter; and
    - at an embedment depth of 0.2 times the culvert diameter.
- To compare the hydraulic conditions, including flow depths, velocities and turbulence intensities, found within a culvert placed at grade to those found within a culvert placed at two different degrees of embedment.

1.3 Scope of Work

The research program was undertaken through the use of a physical hydraulic model. The hydraulic conditions in the model culvert barrel were altered by using combinations of the following:

- The culvert invert placed at grade, at 0.1 times the culvert diameter (0.1*D*) below the bed grade level, and at 0.2*D* below the bed grade level, and
- Three discharges of 50 L/s, 70 L/s and 90 L/s.

The culvert slope was set at approximately 0.75% for all tests. The tests consisted of a culvert barrel that did not have any backfill material or baffle structures. Only part-full flow conditions were studied. A single size of culvert with a length of 8 m and a diameter of 500 mm was studied.

An in depth analysis regarding turbulence intensities is not part of this research study, instead the data will be presented and brief comments will be provided.

1.4 Organization of the Thesis Document

This thesis document is presented in six chapters, as follows.

Chapter 1 provides background information on culvert fishways and the associated need for research into the hydraulics of embedded culverts with respect to fish passage. The objectives of the research and the scope of work are also outlined in this chapter.

Chapter 2 discusses the knowledge provided from past research, including both lab and field studies. Literature concerning culverts, ichthyomechanics, and culvert baffle systems that has led to current stream crossing design criteria and practices for successful fish passage through culverts is also summarized. Also discussed are the results of new research into culvert velocity distributions, backwater effects, and turbulence that is of use to designers in optimizing the size and shape of stream crossing structures so as to minimize costs without compromising the successful migration of fish.

Chapter 3 describes the experimental arrangements, physical hydraulic model, data acquisition system and equipment used in the laboratory study.

Chapter 4 presents a summary of the hydraulic theories used and applied to this research study. Also included in this chapter are the experimental procedures and methods of data collection.

Chapter 5 presents the processed data and the analysis of the data. A comparison of the results from this work to those found in the literature is also provided.

Chapter 6, the final chapter, summarizes the thesis, highlights the conclusions, identifies the study limitations and offers recommendations for further studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

As a precursor to the study on culvert hydraulics related to fish passage, a literature review was undertaken on culvert fishways. Culverts are used when highways or railways cross rivers or streams. Unfortunately, the use of culverts at stream crossings may hinder the normal migratory cycle of upstream and downstream fish movements. Therefore, in addition to passing streamflow, a culvert must also be designed to operate as a fishway. The knowledge gained from past research, field studies, and literature concerning culverts, ichthyomechanics, and baffle systems has led to current stream crossing design practices for successful fish passage through culverts. The results of new research into culvert velocity distributions, backwater effects, and turbulence will help designers to optimize the size and shape of stream crossing structures so as to minimize costs without compromising the successful migration of fish.

2.2 Culverts as Barriers to Fish Migration

Culverts are engineering structures that allow water to be diverted or permit the flow to continue while the land above the culvert may be developed for other uses, such as roads and rail networks (Liriano et al. 2002). In Western Canada, there are a large number of stream crossings, and culverts are the most popular stream crossing structure because of their lower comparable cost to other alternatives (Katopodis 1992). The culvert may appear to be a simple structure; however, the hydraulic requirements of a culvert may be surprisingly complex due to the large number and wide range of variables that affect culvert flow. These variables include headwater and tailwater depths, inlet geometry, barrel size, culvert shape, length, slope, and roughness of the culvert (Smith 1995).

A series of investigations into the flow of water through culverts has been conducted over the past several decades. The main aims of the early work were to establish the general parameters within which culverts operate and to accumulate an array of entrance, exit, and friction loss coefficients, which subsequently led to improved design methods for culverts (Day 1997). Later, a number of studies looked at the scour at culvert outlets and the effect of changing a number of parameters on the extent of scour (Day 1997). More recently, culverts and culvert hydraulics have been studied because of their impact on fish and aquatic species (Katopodis 1993).

There are several types of culvert. Culvert shapes include round, square, rectangular, elliptical, and arched (Smith 1995). The open bottom arch and box culverts retain natural stream bed material and gradient, and as a result, water velocities are not significantly changed. Open bottom culverts can be designed to maintain the normal stream width up to the fish passage design flow (Katopodis 1993). However, these culvert types are generally more costly and can be limited by foundation considerations. With pipe arch, elliptical, or round metal culverts, baffles can be installed along the pipe invert or the pipes can be embedded. Construction materials include wood, concrete, plastic and corrugated steel (Smith 1995).

Although culverts are commonly used as an inexpensive alternative to bridges, they can also cause problems for fish and other aquatic organisms by disrupting their habitat and potentially causing a barrier that restricts or prevents migration. Fish must be able to move about within a stream system for several reasons such as reproduction, growth, food, escaping predators, and seeking more desirable habitat (Katopodis 1993; Warren and Pardew 1998). The success of a fish in passing through a culvert depends on the hydraulic conditions at the culvert outlet, within the barrel, and at the culvert inlet (Behlke et al. 1991). There are four common conditions that create a migration barrier, including an excess drop at the culvert outlet, high velocities within the culvert barrel or at the culvert outlet, inadequate depth of flow within the culvert barrel, and debris and sediment accumulation at the culvert inlet or internally (Bates 2003). The effects of the stream crossing conditions can be temporal (impassible to fish some of the time depending on flow conditions), partial (impassible to a particular species or life stage at all times) or total (impassible to all fish all of the time) (Lang et al. 2004).

2.3 Ichthyomechanics

2.3.1 Fish Propulsion

Swimming ability is a crucial component in the successful migration of fish; therefore, it is important to understand fish swimming capabilities or the “biologic” requirements of culvert design (Katopodis 1992). Fish propulsion results from swimming musculature activities of red and white muscle systems (Blaxter 1969). The red muscle system is used for long-term activities and is an aerobic state. It is characteristic of slow, continuous swimming with large-amplitude, low-frequency, caudal-fin motions (Moyle and Cech 2004). The white muscle system is used for elevated levels of swimming power for short periods and is an anaerobic state. During white muscle system activity, there is high frequency, small-amplitude, caudal-fin motions (Moyle and Cech 2004). Severe white muscle activity will quickly leave a fish in a state of white muscle exhaustion, and white muscle swimming can not resume until after the fish has rested (Blaxter 1969).

2.3.2 Fish Swimming Capabilities

Fish swimming capabilities have been characterized by the terms burst speed, prolonged speed and sustained speed (Behlke et al. 1991; Katopodis 1992). The white muscle system is used for burst speeds that can be maintained for only 20 seconds or less, while the red muscle system is used for prolonged speeds and sustained speeds, which can be maintained for 30 minutes and indefinitely, respectively (Katopodis 1992). Burst speeds are used to enter culverts that are perched and require a significant jump. They are also used to enter culverts that contain relatively high velocities or to negotiate high velocity zones created by baffles or weirs. Prolonged speeds, which can be maintained for up to 30 minutes, are used to swim the length of a culvert when no resting areas are available (Katopodis 1992). If burst speeds are required to swim the length of the culvert after entry, a fish may exhaust itself before successfully passing through longer culverts (Gregory et al. 2004).

Many studies have focused on swimming ability associated with prolonged and sustained speeds; however, very few provide empirical measures of burst performance (Haro et al. 2004). Of those studies that do measure burst performance, most involve fish swimming against carefully controlled flows within enclosed chambers (Brett 1964) instead of allowing fish to voluntarily navigate large-scale, experimental, open-channel flumes that more closely mimic natural conditions. The latter method allows fish to express normal upstream migratory behaviors (Dow 1962; Weaver 1963). Even with carefully constructed swimming performance studies, such as that of Haro et al. (2004), the swimming ability of fish varies with species, size, age, water temperature, oxygen, pH, and salinity (Katopodis 1993). For example, methods used to assess the barrier status of culverts for adult fish may not directly apply to juvenile fish (Richmond et al. 2007). The ability of fish to traverse velocity barriers has remained poorly quantified.

2.3.3 Swimming Location of Fish

Within a stream, a fish will choose the best location to swim relative to its swimming ability. When choosing a location, fish make compromises among many interacting physical and biotic factors such as water velocity, water depth, substrate, cover, and shade (Cotel et al. 2006). Fish observed in natural channels and culverts often swim along the edge of the cross-section close to the water surface, utilizing regions of lower water velocity and minimal profile drag, as shown in Figure 2.1 (Behlke 1998; Lang et al. 2004). For example, Pearson et al. (2005) constructed a culvert test bed at a hatchery in western Washington State that was used for rearing coho salmon and steelhead trout. The study found that fish successfully reached the upstream end of the culvert predominantly on the right hand side (looking upstream), which suggests that the fish were using the low velocity zone on the right side of the culvert to accomplish passage (Pearson et al. 2005). The reason that the fish predominantly swam on the right hand side was due to the helical pattern of the culvert corrugations causing a slight “swirling” of the flow within the culvert.

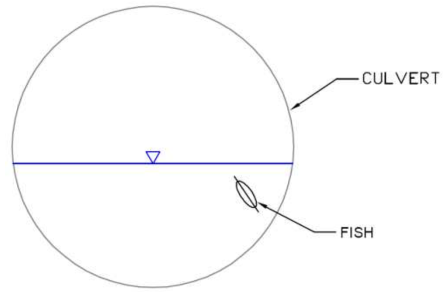

Figure 2.1 Favorable location at the edge of a culvert near the water surface where velocities are lower (reproduced from Behlke 1998).

2.3.4 Flow Turbulence and Fish

Previous studies of fish behavior were commonly concerned with flow velocity; however, recent studies have indicated that fish behavior is also related to flow turbulence, including the importance of Reynolds stresses and eddy sizes (Guiny et al. 2005; Lupandin 2005; Smith et al. 2005; Morrison et al. 2009; Rajaratnam et al. 2010; Silva et al. 2010). Turbulence in rivers is caused by shear on the riverbed as well as by flow separation around blunt objects or cover (Smith et al. 2005).

The first studies of the effect of turbulence on the behavioral response of a fish in a stream showed that the threshold and critical flow rates with which a fish could swim decreased with an increase in the flow turbulence (Lupandin 2005). The mechanism of turbulence impact on fish locomotion was explored with the assumption that balance loss is a factor decreasing fish swimming performance under conditions of high turbulence (Lupandin 2005). Cotel et al. (2006) found that locations occupied by brown trout had lower turbulence intensities than similar locations without brown trout but higher turbulence intensities than is typical of an average stream. Silva et al. (2010) investigated the effects of velocity and turbulence on fish behavior by means of an indoor full-scale pool-type fishway with a cyprinid species, the Iberian barbel (*Luciobarbus bocagei*). They found very good correlation between the horizontal component of Reynolds shear stress and fish transit time, highlighting this variable as a key-parameter which strongly determines the movements of Iberian barbel.

Smith et al. (2005) measured turbulence at the positions of juvenile rainbow trout in a laboratory flume and found that those positions were characterized by low turbulence levels across a range of velocities that the fish could navigate. However, they found that the fish would occupy highly turbulent locations if mean cross-sectional velocities of the culvert were nearing the fish's swimming capability. In other words, the fish preferred low turbulence areas unless the velocities where too high, in which case they would swim in the highly turbulent locations of lower velocity.

Recently, detailed experimental studies of turbulent flows generated around fish protection structures have been conducted; the results can then be used for assessing fish behavior related to turbulence. For example, Tarrade et al. (2011) studied the kinematics of hydrodynamic turbulent flow developed in vertical slop fishways using Particle Image Velocimetry, while Rajaratnam et al. (2010) presents the turbulent flow measured near a vertical angled fish screen. Morrison et al. (2009) measured the turbulent flow structure inside a full-scale spiral corrugated culvert fitted with sloped- and slotted-weir baffles, however, no significant relationships could be found between the turbulence results of the study and the biological fish passage tests performed at the same experimental site due to the lack of substantial differences in streamwise and lateral turbulence intensity distributions downstream from the baffles.

2.4 Current Culvert Design Criteria for Fish Passage

With the growing concern of aquatic environments and legislation such as the Fisheries Act (R.S., 1985, c. F-14), culverts must be designed to satisfy (1) the "hydraulic" requirements of safely conveying water from one side of a roadway embankment to the other, and (2) the "biological" requirements of maintaining successful movement of fish within a stream. Therefore, if a stream is deemed to be fish bearing where the proposed culvert is to be installed, the culvert must be designed to prevent the occurrence of fish passage barriers.

There are commonly three main criteria for the design of culverts for fish passage: (1) maximum culvert flow velocity that fish can negotiate; (2) maximum period for which fish may be delayed; and (3) minimum depth of water within the culvert barrel (SHT 1989).

The basic velocity criterion generally references curves that were developed to show the relationship between water velocity and swimming distance for various fish lengths (Katopodis 1992). Separate curves have been created for anquilliform (eel-like form in which most or all of the body takes part in propulsion) and subcarangiform (trout-like form in which most of the motion is in the posterior half or third of the body) swimming fish. For a given fish species, fish length and swimming distance, these curves can provide the water velocity against which the fish is capable of swimming. These curves were developed using a broad range of published data (over 500 references) on fish swimming performance that contained large data gaps for most species (Katopodis 1992). These curves are interpreted as mean values. Further, the published data were based mostly on laboratory tests in an optimum water temperature range, and therefore, may not accurately represent natural swimming capabilities (Alberta Transportation 2001). This velocity criterion represents an initial effort at providing for quantitative information with which to undertake hydraulic design. The velocity criterion is usually specified in terms of mean flow velocity (MNR and DFO 1996; SE 1995), which does not account for a fish's natural ability to seek out sufficiently low velocity regions.

With respect to the maximum delay criterion, each regulatory jurisdiction has its own criterion. For example, Saskatchewan Environment's *Fish Habitat Protection Guidelines* (1995) state that "the period during which the culvert is impassable to fish should not exceed three days with a one in ten year flood frequency". Similarly, Alberta Transportation's *Fish Habitat Manual* (2001) states that "a fish passage delay should not exceed three days more than once every 10 years". Manitoba Stream Crossing Guidelines for the Protection of Fish and Fish Habitat (MNR and DFO 1996) has a slightly different criterion which states that “the crossing should not be impassable for longer than seven consecutive days once in 50 years”.

Fish passage during low flow conditions is achieved by providing a sufficient water depth. Again, each regulatory jurisdiction has its own criterion. In Alberta, this is generally achieved by “depressing the culvert invert to a depth of D/4, at least 0.5 m and up to 1 m below the stream channel thalweg” (Alberta Transportation 2001). Saskatchewan Environment’s *Fish Habitat Protection Guidelines* (1995) states that “the depth of flow in the culvert should not be less than 200 millimeters to allow the passage of adult fish during low flow periods”.

Although the intent of all of the design criteria is to provide for passage of the weakest fish in a stream, the conservatism built into each criterion is generally compounded. The conservatism results in unnecessary project costs. As stated by Lang et al. (2004), “Cumulatively, this conservatism may result in overly conservative design criteria that offer no additional benefit but force an unnecessary increase in project complexity and cost, and may invalidate the credibility of the responsible agency”.

2.5 Design Methods to Meet Fish Passage Criteria

2.5.1 Stream Simulation Design Approach

Stream simulation design focuses on sizing and installing culverts to avoid constricting the stream or river channel. Where culverts can be installed with the same slope as the natural streambed, non-constricting culverts will normally provide water depths, velocities, bottom substrates and channel characteristics that are comparable to the natural stream (House et al. 2005). Well-designed culverts can maintain the continuity of the stream bottom and hydraulic conditions, and provide unimpeded transport of bedload and debris, thereby facilitating passage for most aquatic organisms using the stream. An open bottom arch or open bottom box culvert can accommodate the stream simulation design approach. Typically, structures that span the stream channel without affecting fish habitat and natural channel dynamics are the preferred structure for protecting fish and fish habitat (DFO 2005).

The stream simulation method is costly due to the large spans generally required to avoid constricting the stream, and it can be limited by foundation considerations (Alberta Transportation 2001). The design criteria for stream simulation culverts are generally based on matching the local stream geomorphology and not on flow velocities and depths. However, current criteria are somewhat preliminary and will be revised as experience with streambed simulation accrues (House et al. 2005).

2.5.2 Increasing the Culvert Cross-Sectional Area

A common method of satisfying the fish passage velocity criterion is to increase the cross-sectional area of the flow, which then decreases the mean velocity of the flow for a given discharge. Increasing the cross-sectional area can be done by increasing the size of the culvert; however, one large pipe often permits the flow to spread out at low flows to the point where there is insufficient water depth for fish to swim (Clay 1995). This can be overcome by installing multiple barrel culverts, but the effectiveness of multiple culverts is questionable because fish need to choose which culvert to enter. Fish have been observed choosing the culvert with the most flow and highest velocity (Baker and Votapka 1990 as cited by Alberta Transportation 2001). Therefore, it is preferable to use fewer (or a single) culvert rather than multiple smaller culverts (Alberta Transportation 2001). Either increasing the size of the culvert or installing multiple culverts can significantly increase the cost of the culvert installation.

2.5.3 Embedding a Culvert

Depressing a culvert invert below the streambed (which is also known as embedding a culvert) can provide for increased flow depths and reduced barrel velocities by increasing the flow area, given the culvert is flowing part full. The embedded culvert can be designed with or without fill material placed along the invert (i.e., backfilling). Three general types of embedded culverts exist as shown in Figure 2.2: (1) the culvert invert elevation is lower than the streambed and there is no fill material in the barrel, (2) the elevation of the fill material is equal to the stream bed elevation, or (3) the elevation of the fill material is lower than a streambed elevation (Alberta Transportation 2001).

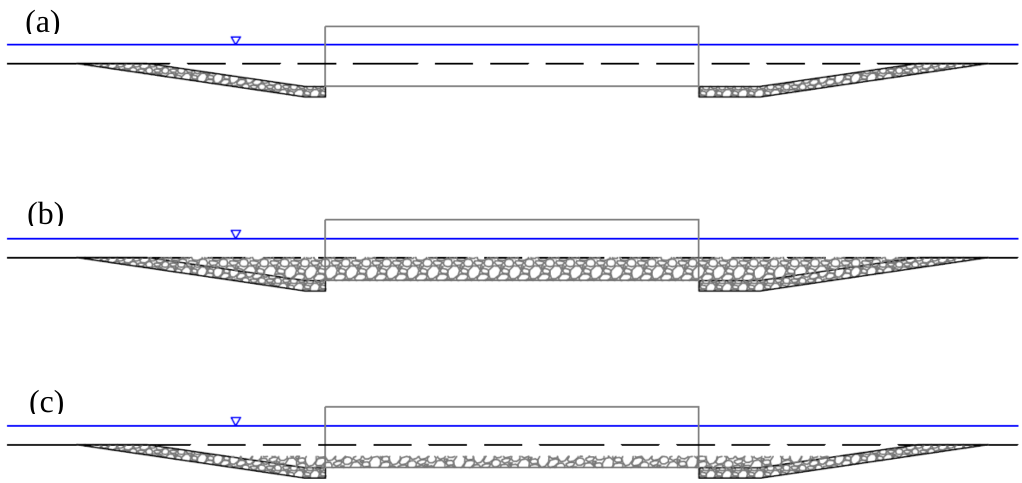

Figure 2.2 Schematic illustrations of culvert embedment types: (a) embedded without backfill, (b) embedded with backfill elevation equal to stream bed elevation, and (c) embedded with backfill elevation less than stream bed elevation (Alberta Transportation 2001).

Material along the culvert invert provides natural substrate for aquatic organisms and can increase the roughness. Velocities can be reduced if the roughness is greater than that of the side corrugations (Behlke et al. 1991). Several studies have been conducted on the velocity distribution within embedded culverts with backfill material. For example, Magura (2007) and Knight and Sterling (2000) conduced model tests to examine the velocity distribution within an embedded culvert with backfill material. House et al. (2005) conducted a field study where cross-section velocity measurements were taken at the middle and outlet ends of six embedded culverts with continuous gravel beds. All three studies indicated that further studies were required to better predict the effect of embedment on the velocity distribution in circular culverts under open channel flow conditions.

Embedding a culvert below the stream bed elevation is a commonly used method in the prairie provinces. For example, embedded culverts are described in Alberta Transportation's *Fish Habitat Manual* (2001) as a method of mitigating the effects of culverts on fish passage. Further, *Manitoba Stream Crossing Guidelines for the Protection of Fish and Fish Habitat* (1996) state that culverts should be installed "a minimum of 30 cm or 10% of culvert diameter (whichever is greater) below the normal stream bed". Saskatchewan Environment also states that "culverts should be embedded a minimum of 200 millimeters below the natural channel bed elevation" (SE 1995).

2.5.4 Culvert Baffles

Culvert baffles provide hydraulic obstructions at regular intervals that dissipate energy, increase overall effective roughness, create turbulent flow, and provide potential resting zones for fish (Alberta Transportation 2001). However, baffles also reduce culvert conveyance capacity, require frequent maintenance and routine inspection, and create an artificial environment where a fish must use its burst speed. Therefore, there is some controversy as to whether baffles should be used in new culvert installations. Gregory et al. (2004) conducted a study on fish movement at several culverts within Oregon that were retrofitted with baffles. The observations indicated that fish can and do move through culverts retrofitted with baffles and that the addition of baffles can improve the ability of juvenile fish to move upstream through a culvert (Gregory et al. 2004). Lang et al. (2004) confirmed through visual observation and PIT tag scans from a culvert evaluation study that fish use the low velocity regions created by the baffles for resting.

There has been extensive study on different types of culvert baffles conducted at the University of Alberta (Rajaratnam et al. 1988; Rajaratnam et al. 1989; Rajaratnam and Katopodis 1990; Rajaratnam et al. 1990; Rajaratnam et al. 1991). These studies, which were based on laboratory experiments, investigated the hydraulics of the offset baffle, slotted-weir baffle, weir baffle, spoiler baffle, and the Alberta fish weir and baffle system. Figure 2.3 shows a schematic illustration of several different baffle systems. Ead et al. (2002) presented a comprehensive analysis of the experimental observations of these studies. They found that a general correlation exists between the dimensionless discharge and the relative depth of flow for each value of the relative baffle height. Also found in their study was that, even though most of the baffle systems worked reasonably well over the range of parameters recommended, the weir and slotted weir baffle systems are simpler yet resulted in flow hydraulics that appeared equally effective.

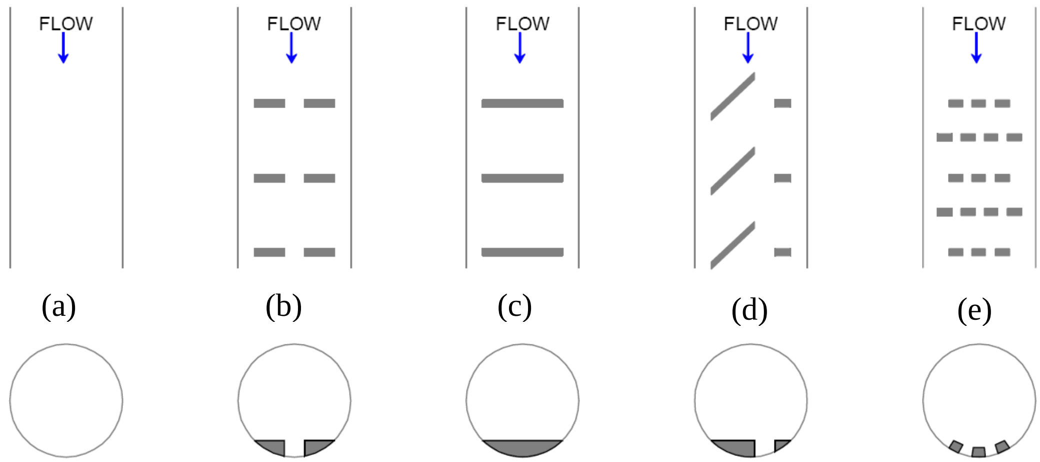

Figure 2.3 Schematic illustrations of different culvert baffle systems (reproduced from Katopodis 1992): (a) plain, (b) slotted weir, (c) weir, (d) offset and (e) spoiler.

Broadfoot and Murphy (2002) evaluated the effectiveness of baffle structures as fish habitat compensation for ten culverts in southern Ontario during 2002 and 2003. They found that baffles facilitated fish passage but only for large fish with relatively high velocity swimming capabilities. Therefore, most fish that inhabited the small stream, where baffle modifications occurred, were too small to successfully pass through the entire length of the culverts in the system.

Katopodis et al. (1978) conducted a study of culvert baffling for fish passage at the Mackenzie Highway crossing of the Redknife River. They compared the flow area available at different water velocities within a cross-section for baffled culverts and non-baffled culverts. They found that the addition of baffles did improve the availability of low velocity zones, although such areas were small and their size was highly variable along the culvert length and among baffle configuration.

2.6 Velocity Distribution Within Culverts

2.6.1 Zones Occupied by Fish

Observations of fish movement indicate that the zones occupied by fish when traveling upstream through a culvert can be relatively localized; they do not include the full cross-section (House et al. 2005). Studies have also shown that fish have a natural ability to find the low velocity zones that occur near the culvert boundaries. For example, Behlke et al. (1991) studied fish swimming location preferences at two culvert locations in the field and observed that many grayling and other fish species seek and find the best locations for swimming, as judged by inference. The authors concluded through observation that the easiest location for fish to swim is at the edges of the cross-section close to the water surface where water velocities are lowest. Lang et al. (2004) conducted a three-year detailed field study of fish passage and the hydraulics encountered by migrating fish at culvert stream crossings in northern California. The study found that the velocities along the culvert walls were generally far lower than those velocities in the center of the flow. These observations gave rise to model studies, such as this research study, of the velocity distribution in a culvert so that the extent of the occupied zone could be estimated during the design process (Ead et al. 2000; House et al. 2005; Pearson et al. 2005; Magura 2007).

2.6.2 Velocity Prediction Equations

Transverse velocity distributions in open channel flow have been modeled in equation form in one and two dimensions. The classic one-dimensional vertical velocity distribution, known as the Prandtl-von Karman velocity distribution law, has a logarithmic form (Chow 1959), expressed as

[2.1] $$u = 2.5u_* \ln\left(\frac{z}{z_o}\right)$$

where: u is the x-direction (i.e. streamwise) velocity (m/s) at z,

z is the vertical distance above the bed (m),

u_* is the shear velocity found by $\sqrt{gR_hS}$ (m/s),

g is the acceleration of gravity (m/s^2),

R_h is the hydraulic radius (m),

S is the slope of the energy grade line (m/m), and

z_o is a constant (m) related to the bed roughness element size.

The Prandtl-von Karman velocity relationship, sometimes referred to as the log-law relationship, was adapted to describe hydraulically smooth, transitional and rough flow regimes in boundary layers. The equation for the rough flow regime is

$$[2.2] \qquad \frac{u}{u_*} = 5.75 \log\left(\frac{z}{k_s}\right) + 8.5$$

where k_s is the Nikuradse equivalent sand grain roughness height.

White (1996) extended the use of the one-dimensional logarithmic velocity distribution to predict velocity distributions in embedded culverts in Oregon that were backfilled with substrate material. Assuming that the cross-sectional area was approximately rectangular in shape, multiple normalized velocity profiles were taken across the channel and used to develop, using regression, an average distribution. This distribution was used to compute the percent channel area that was below a given allowable fish passage velocity assuming the channel to be a wide channel. White (1996) found that the computed percentages of channel area were generally conservative (i.e., under-estimated) since there were additional low velocity areas of the cross-section near the sides of the channel.

House et al. (2005) further developed the regression approach of White (1996) for velocity distributions in embedded culverts that were backfilled with gravel material. The data collected from six stream crossing culverts in Oregon were transformed into isovels at 7.6 cm/s intervals. The cross-sectional area between the isovels was then expressed as a cumulative percentage of the total cross-sectional area. A logit transformation was used to make the velocity distributions more linear, and prevent the computational occurrence of negative velocities and areas greater than 100 percent (House et al. 2005). Regression analysis was used to determine the slope of the transformed velocity distribution using velocity values normalized using the average velocity. House et al. (2005) concluded that the accuracy of the proposed model for culverts embedded and backfilled with gravel material appears quite good; however, the overall objective of the study was to simply show the potential of the modeling approach.

Ead et al. (2000) conducted a laboratory study on the velocity distribution in turbulent open-channel flow in a circular corrugated pipe placed at grade and devised equations used to delineate the velocity distribution. The authors used an 8 m long pipe having an average diameter of 0.622 m and annular corrugations with amplitude of 12 mm and a wavelength of 68 mm. Discharges ranged from 30 L/s to 200 L/s, while the culvert slopes were 0.55%, 1.14% and 2.55%. Centerline velocity and water surface profiles were taken at 14 stations along the length of the culvert. Velocity profiles were also measured at six non-central locations at station 8 (a location where the flow was fully developed) for all of the discharges and for each of the three slopes. A pitot tube was used to make velocity measurements. All velocity profiles were described by the Prandtl-von Karman equation of rough turbulent flow (Equation 2.2); however, the profiles in the non-central planes had a significant deviation from the linear line described by the Prandtl-von Karman equation in the upper part of the flow. These deviations in the velocity profile were strongly correlated with the relative distance from the central plane. The deviations from the linear line described by the Prandtl-von Karman equation were hypothesized to be a result of secondary currents. Therefore, Equation 2.2 was expanded to account for the non-central deviations, and the resulting equations are

[2.3] $$\frac{u}{V}=\left[\frac{2.30}{\kappa}\log\left(\frac{z_y}{k_s}\right)+8.50\right]\sqrt{f_3\left(\frac{y}{y_o}\right)\left(\frac{Jn\sqrt{g}}{R_h^{1/6}}\right)}$$

for $\frac{z_y}{k_s} < \frac{z_d}{k_s}$

[2.4] $$\frac{u}{V} = \left[\frac{2.30}{\kappa}\log\left(\frac{z_y}{k_s}\right) + 8.50 - \frac{(z_y/k_s) - f_1(y/y_o)}{(Z_y/k_s) - f_1(y/y_o)} \times f_2(y/y_o)\right]\sqrt{f_3\left(\frac{y}{y_o}\right)}\left(\frac{Jn\sqrt{g}}{R_h^{1/6}}\right)$$

for $\frac{z_y}{k_s} > \frac{z_d}{k_s}$

where

[2.5] $$f_1\left(\frac{y}{y_o}\right) = \frac{z_d}{k_s} = -6.91\left(\frac{y}{y_o}\right)^2 - 2.05\left(\frac{y}{y_o}\right) + 9.00$$

[2.6] $$f_2\left(\frac{y}{y_o}\right) = \frac{\Delta u_m}{u_*} = 5.58\left(\frac{y}{y_o}\right) + 0.90$$

[2.7] $$f_3\left(\frac{y}{y_o}\right) = \frac{\tau_0}{\tau_\infty} = -20.00\left(\frac{y}{y_o} - 0.60\right)^3 + 2.75\left(\frac{y}{y_o} - 0.60\right)^2 - 0.40\left(\frac{y}{y_o} - 0.60\right) + 1.00$$

[2.8] $$J = \frac{u_{*o}}{\sqrt{gR_hS}}$$

where: V is the mean velocity of the flow (m/s),

z_y is the height above the datum at a non-central plane (m),

y is lateral distance from the central axis of flow (m),

J non-dimensional parameter

n measure of boundary resistance referred to as Manning's n

y_o is half the top width of flow (m),

Z_y is the average depth of flow at a non-central plane in the uniform flow region (m),

z_d is the height above culvert invert at which the velocity profile readings deviate from Equation 2.2 (m),

Δu_m is the maximum deviation in velocity from Equation 2.2 in the upper region of the flow (m/s),

τ_o is the bed shear stress at relative distance y/y_o (N/m²),

τ_∞ is the bed shear stress at the central axis (N/m²), and

u_{*o} is the shear velocity at the central axis (m/s).

The general findings of this study agreed with the velocity measurement observations made in a large corrugated pipe having a diameter of 4.27 m with two slopes of 0.14% and 1.42% (Ead et al. 2000). With respect to the secondary currents, Papanicolaou and Talebbeydokhti (2002) state that “To adequately describe the secondary nature of a flow (within a culvert), it will be more appropriate to provide measurement of the transverse and vertical velocity distributions as well as a detailed description of the turbulen[ce] intensities”.

2.6.3 Effect of Backwater on Fish Passage

Backwater is the rise of water level upstream due to an obstruction or constriction in the channel. Backwater through a culvert can be created using series of rocky ramps and pools downstream of the culvert outlet. Backwater can also be created by embedding a culvert and not backfilling it with gravel material. In this case, the water level in the channel downstream from the culvert would be equal to approximately normal depth. So, if the culvert invert is embedded below the bed elevation, then the effective culvert tailwater depth is greater than the normal flow depth within the culvert causing a rise of water level as the water flows through the culvert. Backwater can only be created for part-full flow conditions.

Backwater can be used to remove a vertical drop and to reduce the velocity of flow passing though a culvert. Lang et al. (2004) studied an elliptical corrugated steep pipe that was embedded on Cow Creek in California. This culvert had a downstream control consisting of a gravel berm that created backwater. From comparison of isovels of other culverts to the Cow Creek culvert, they found that the backwater can substantially reduce the peak velocities within the culvert.

2.7 Summary of Literature

From the review of the literature, several conclusions can be made with respect to culvert hydraulics and fish passage. Firstly, the “biological” component of culvert design is still not completely understood. Understanding fish swimming abilities with respect to velocities and turbulence is an on-going research effort. It appears that the majority of past research used artificial environments to test fish swimming capabilities, which may not accurately represent the capabilities of fish in their natural environment. Moreover, the research effort is not equal among fish species; therefore, the swimming abilities of some species are not well known. Current fish passage design criteria seem to be very conservative due to a lack of biological information; therefore, more research into the natural swimming ability of fish is needed for several species of fish.

Secondly, there appears to be a lack of field research that combines fish passage effectiveness (the biologic component) with velocity and depth measurements (the hydraulic component). Therefore, more monitoring should be conducted on culvert fishways to evaluate the effectiveness of fish passage through culverts.

Thirdly, there have been recent studies on the velocity distribution within culvert barrels; however, these studies focused on culverts that were backfilled with substrate material or culverts that were placed at grade. There appears to be no published research efforts focusing on quantifying the velocity distribution within embedded culverts that have not been backfilled. There is little research focusing on the effect of backwater or baffles on the velocity distribution within culverts.

Lastly, with newer velocity measurement technology, flow turbulence is becoming a more researched topic with respect to fish passage and fish protection structures. However, very little research combines the flow turbulence measurements with the fish behavior related to the flow turbulence.

CHAPTER 3

EXPERIMENTAL ARRANGEMENTS AND INSTRUMENTATION

3.1 Laboratory Facility

The physical model study of the culvert installation reported herein was conducted in the Hydrotechnical Laboratory of the Department of Civil and Geological Engineering at the University of Saskatchewan. The experimental arrangement was independent of other laboratory systems, which provided for greater control over water temperatures, discharges, and turbidity. The study used a 1.21 m wide, 0.61 m deep and 20 m long rectangular flume having a recirculating flow system served by a 30 hp, variable-speed, centrifugal pump located at the downstream end of the flume. The maximum capacity of the pump is 2500 US gallons per minute (157.7 L/s). The working section of the flume is constructed of an aluminum floor at zero slope with one Plexiglass sidewall for most of its length to facilitate visual observations. The flow depth was controlled by a vertical-leaf gate that spanned the full width of the flume. The discharge within the system was controlled by increasing or decreasing the pump speed. A schematic illustration of the test system is shown in Figure 3.1.

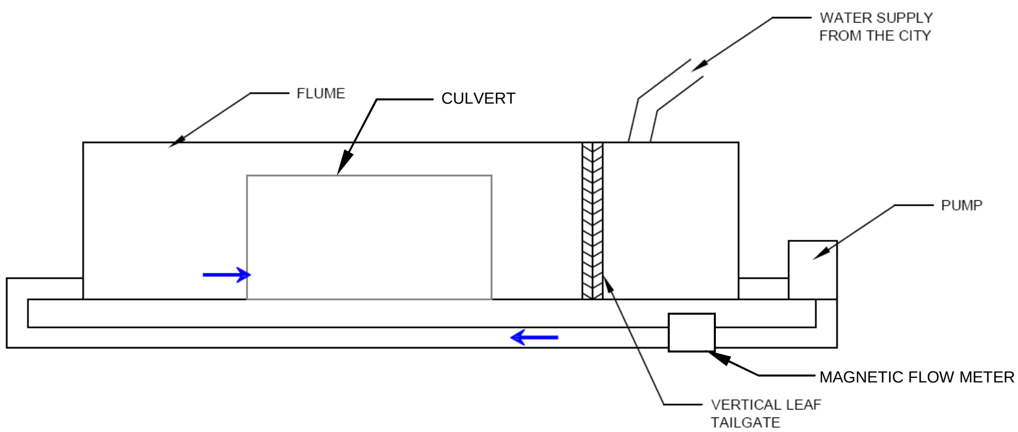

Figure 3.1 Schematic illustration of the model culvert test system.

3.2 Physical Model of Culvert Installation

3.2.1 Model Development

The physical model of the culvert installation was a Froude model; however, it was not developed to any particular scale. Instead, the size of the model was selected sufficiently large so that Reynolds and Weber effects were assumed to be negligible. The diameter of the model culvert was limited by the physical dimensions of the flume and the estimated headwater depths required to operate the model. It was determined that the maximum culvert diameter that could physically fit into the study flume and for which the water would not overtop the flume walls during testing was 500 mm.

An 8 m long circular annular corrugated steel culvert with 13 mm x 68 mm corrugations was used for the model culvert. Manufacturer dimensions were confirmed and are listed in Table 3.1. A diameter of 500 mm was used for calculation purposes. Annular corrugations were used to avoid the scale effect associated with a small-scale helical pipe and to properly represent the corrugation alignment most often found in large diameter culverts. For example, the helix angle on a large scale culvert, such as a 3000 mm diameter culvert, is very near to 90 degrees (or annular) due to the fabrication process. Using a small-scale culvert with helical corrugations would cause a non-level transverse water surface profile due to the spiraling of the flow. In other words, the water would ride at a higher elevation on one side of the culvert than the other and surface cross flow would occur from the high side to the low side. The length and type of culvert used in this work was the same as that used in a similar study by Ead et al. (2000).

Table 3.1 Measured model culvert dimensions.

Measurement	Diameter Upstream End (mm)	Diameter Downstream End (mm)	Corrugation Amplitude (mm)	Corrugation Wavelength (mm)
1	509	488	13	68
2	506	492	13	68
3	501	494	13	69
4	-	-	14	67
Mean	505	491	13	68

From tests conducted in the laboratory, the Manning's *n* value of the model culvert was found to be 0.024, which is in agreement with commonly published values for annular corrugated steel pipes (CSP) (e.g., CSPI 2002). Details of the tests conducted to determine Manning's *n* values are shown in Appendix A.

The study involved only part-full culvert flow to a maximum flow depth of 72% full. Access holes approximately 300 mm by 100 mm in size were cut into the crown of the culvert at 15 locations along its length to permit access to the flow within the culvert, as shown in Figure 3.2. The holes were numbered 1 through 15, with 1 being the hole closest to the inlet. Hole 9, located approximately 5 m from the culvert inlet, was larger in size to accommodate greater access to the flow, as shown in Figure 3.2.

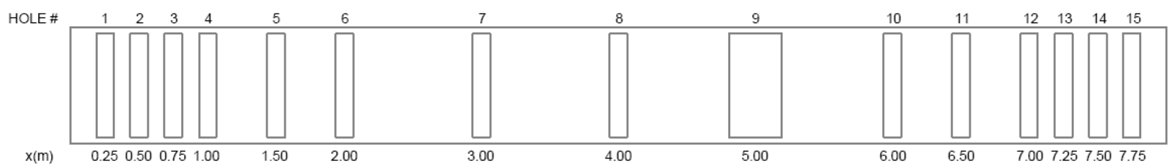

Figure 3.2 Plan view of culvert showing location and size of culvert access holes.

3.2.2 Model Coordinate System

A Cartesian coordinate system was used for the model culvert such that the origin was located at the invert of the culvert inlet, regardless of embedment level. Therefore, the x-axis was along the length of the culvert (i.e., longitudinal or streamwise direction), with $x = 0.0$ m being at the inlet and $x = 8.0$ m being at the outlet. The y-axis was the transverse direction of the culvert. The z-axis was the vertical axis, such that the culvert invert was at $z = 0.0$ m and the crown was at $z = 0.5$ m. Figure 3.3 is a schematic illustration of the model culvert coordinate system.

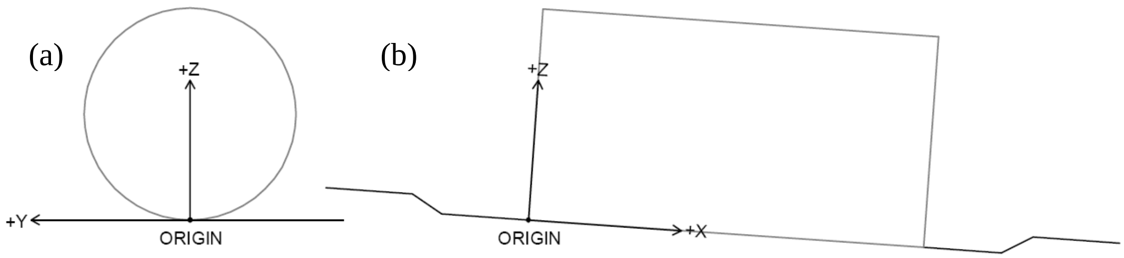

Figure 3.3 Schematic illustrations of the model coordinate system (a) looking downstream and (b) in profile view.

3.2.3 Culvert Installation in the Flume

The model culvert was supported by five equally-spaced wooden supports that were secured to the flume floor and walls, as shown in Figure 3.4. The downstream-most support elevation was fixed, while the four remaining supports were adjustable in elevation. The wooden supports were adjustable to accommodate the increase in distance between the culvert and the flume floor moving upstream due to culvert slope. The most upstream and downstream supports also acted as water barriers so that water was not able to pond beneath the culvert, which would cause culvert buoyancy problems during model operation. Figure 3.4 shows the model culvert being placed into the flume and its final installation.

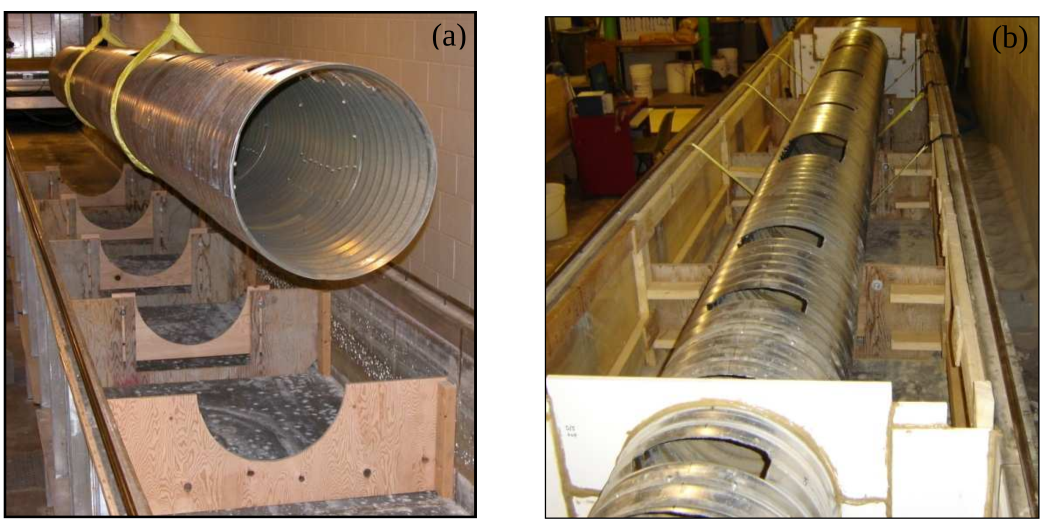

Figure 3.4 Photographs, viewing upstream, of the model culvert (a) being placed on the supports and (b) installed in the flume.

To simulate an actual culvert installation with riprap, the model included a region of rock extending one times the culvert diameter (1D) upstream and three times the culvert diameter (3D) downstream of the culvert inlet and outlet, respectively. Based on an estimated maximum outlet velocity of 1.3 m/s, it was determined that a median rock diameter of 40 mm would be sufficient. Figure 3.5 show the rock at the culvert outlet.

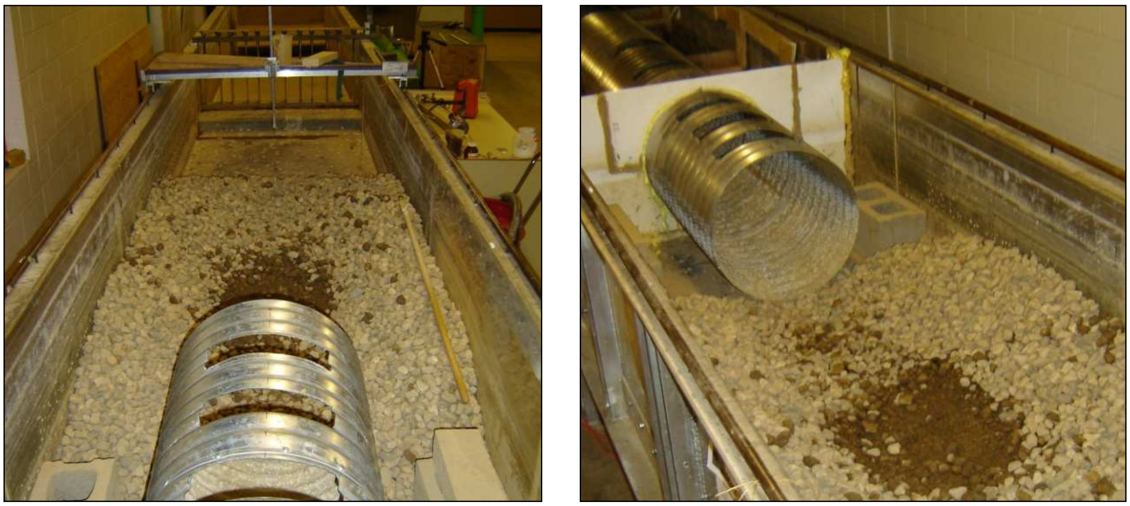

Figure 3.5 Photographs of the model culvert riprap at the outlet.

3.3 Instrumentation for Hydraulic Measurements

3.3.1 Instrumentation Overview

As outlined in the objectives of this study, the hydraulic characteristics of interest are the flow depths, velocity distributions and turbulence intensities found within the model culvert placed at-grade and at different degrees of embedment. Therefore, the following instruments were used:

- A magnetic flow meter installed in the supply line to the flume for measuring the discharge;
- A Sontek Micro-Acoustic Doppler Velocimeter (ADV) to measure point velocities in three dimensions, at a high enough sampling rate to also allow quantification of turbulence intensities;
- A mercury thermometer to measure water temperature; and
- A point gauge to measure the flow depths.

3.3.2 Discharge Measurements

A magnetic flow meter was used to measure the discharge in the test flume. Because it did not have digital discharge readout, a digital multi-meter was connected to the magnetic flow meter to display the voltage reading. An existing relationship between discharge and voltage was verified using a V-notch and a rectangular sharp-crested weir. A linear relationship was found for the calibration curve with an R^2 value of 0.999, as shown in Figure 3.6. The trendline was not forced through the origin due to a residual voltage reading. Details of the calibration are given in Appendix B.

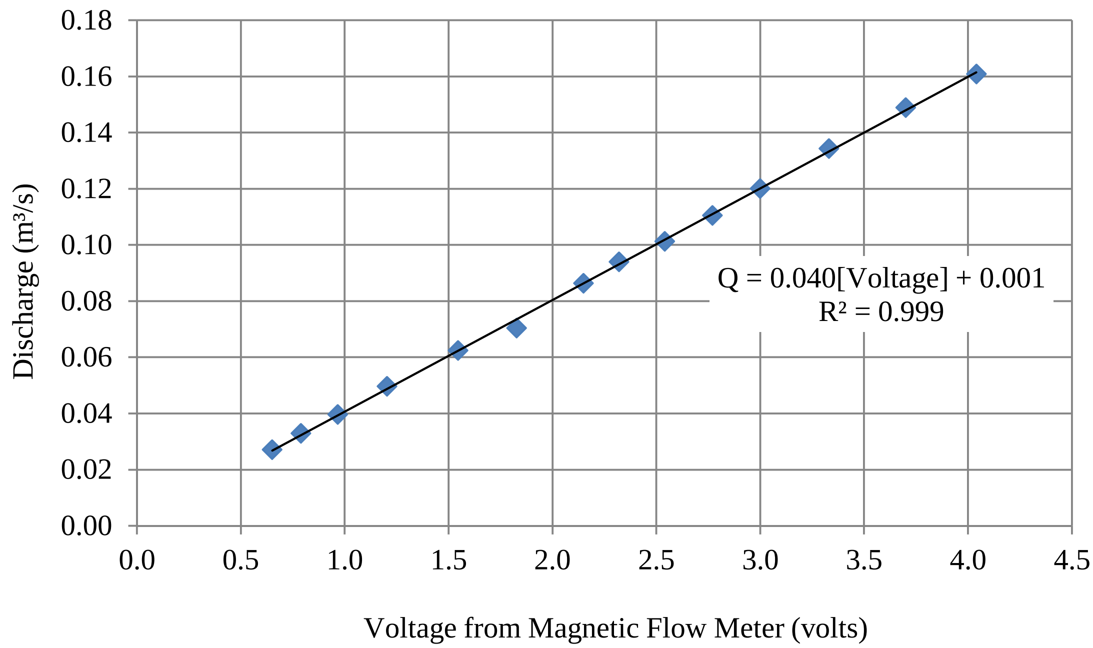

Figure 3.6 Calibration curve for the magnetic flow meter.

From the calibration curve, it was determined that discharges of 50 L/s, 70 L/s and 90 L/s would require voltages outputs from the magnetic flow meter of 1.23 times, 1.73 times and 2.23 times the voltage, respectively.

The accuracy of the discharge through the model culvert was affected by the accuracy of the voltage reading, the sharp-crested weir equations for the rectangular and v-notch weirs, and any minor leaking that occurred through the support barriers or within the culvert. Typical digital multi-meters have accuracies of approximately 0.1% or better, while the weir equations have been extensively studied and documented (i.e., Chow 1959). Minor leaking occurred at the culvert rivets and from both water barriers; however, the leakage rate was constantly monitored and remained only a small percentage of the total discharge. Therefore, it is estimated that the accuracy of the discharge values in this research study are within one percent.

3.3.3 Velocity Measurements

Velocity measurements were taken using a Sontek down-looking three-dimensional ADV. This ADV probe had the ability to measure three-dimensional velocities at a sampling rate of 25 Hz. The acoustic sensors consisted of three acoustic receivers and one acoustic transmitter. The volume of water (approximately 0.3 cm^3) in which the ADV made velocity measurements was located 5 cm from the acoustic transmitter; therefore, the ADV was incapable of taking measurements within 5 cm of the water surface.

The ADV is designed to measure velocity as rapidly as possible, with a single estimate of the three-dimensional velocity field being referred to as a ping. The ADV pings 150 to 250 times per second depending on the velocity range setting (Sontek 2005). Because the noise in a single ping is too high for practical use, the ADV averages a number of pings to reduce the noise level in each output velocity sample. The number of pings averaged is defined by the sampling rate. For this study, a sampling rate of 25 Hz was used. Therefore, the ADV collected as many pings as possible over a 40 millisecond period, averaged the values together, and output the average as one sample.

There are two main factors that add to the uncertainty of the velocity data measured by the ADV: noise and probe geometry. Under good operating conditions, the noise in the ADV horizontal (i.e., streamwise and lateral) velocity data are estimated at 1% of the velocity range when outputting at 25 Hz. For example, individual samples at 25 Hz will have horizontal velocity noise of about ±1 cm/s if using the ±100 cm/s velocity range or about ±0.3 cm/s if using the 30 cm/s velocity range (Sontek 2005). Noise in horizontal velocity (x-velocity and y-velocity) measurements is larger than in vertical velocity (*z*-velocity) measurements by about a factor of four because the axes of the ADV receivers are 15^{o} off the vertical axis. Probe geometry is calibrated at the factory for each ADV, and the accuracy of the velocity data resulting from probe geometry is specified to ±1.0 % of the measured velocity. Note that sound speed also affects the accuracy of the velocity measurements. Speed of sound in water is primarily a function of temperature and salinity. For this research study, temperature of the water was measured using a mercury thermometer, and the salinity of the water was estimated. Errors in sound speed are typically very small and can be corrected in post-processing.

The ADV sends out acoustic waves that must bounce off of particulate matter in the flow. In a lab setting, water is usually quite clean and requires artificial introduction of particles, called seeding. However, for this research study, the model culvert riprap was dirty enough to create enough particulate matter within the recirculating flow system and there was an inherent assumption that this particulate matter represented the actual flow velocity condition. Therefore, additional seeding material was not necessary. Proper seeding of the flow was indicated by the signal-to-noise ratio measured by the ADV.

When using the ADV, it was important to determine the sampling duration required for an accurate mean velocity reading. Choosing a long sampling duration provides enough samples that, when averaged, the results converge towards the true mean velocity value; however, such an approach has considerable implications in terms of the time it takes to carry out a test. Therefore, to determine an appropriate sampling duration for this work, the ADV was used to collect velocity data for various flow conditions within the culvert. Several sampling rates and durations were investigated. Relationships between the mean velocity in the *x*-direction and sampling duration were plotted. Also plotted were the relationship between the root-mean square (RMS) of the velocity in the *x*-direction and the sampling duration. From these relationships, it was found that a sampling duration of at least six minutes was required before the mean velocity or RMS values became constant. For the model study, a sampling duration of 10 minutes was used to ensure accurate results. Details regarding the sampling rate investigation are given in Appendix C.

3.3.4 Measurement Trolley and ADV Apparatus

The flume was equipped with a trolley that could traverse the length of the flume. The trolley had four wheels that sat on two rails along either side of the flume. The legs for the trolley were adjusted so that the trolley sat at a slope equal to that of the culvert. This ensured that the trolley was orientated parallel to the *x*-axis of the model culvert and that of the ADV probe was normal to the streamwise flow direction. Both the ADV probe and point gauge were mounted on the trolley. The point gauge was used to measure the depth of water within the culvert to the nearest 0.02 cm.

The ADV was mounted on the trolley using an apparatus that had the ability to rotate and position the ADV probe within a cross-section of the culvert (i.e., the *y*-*z* plane). The ADV was automatically positioned within a pre-set measuring grid using a LabVIEW program. The probe positioning was accurate to within a few millimeters. Figure 3.7 shows the trolley with the ADV apparatus attached.

Figure 3.7 Photographs of the ADV mounted on the measurement trolley.

The location of the point velocity measurement within the culvert coordinate system was found using trigonometry using the known angle of rotation and location of the ADV on the automated slider. The specific method is described in Chapter 4.

CHAPTER 4

HYDRAULIC THEORIES AND EXPERIMENTAL METHODS

4.1 Hydraulic Theories Applied to Research Study

4.1.1 Uniform Flow

For this research program, part-full flow conditions were studied (i.e., a free surface existed throughout the length of the culvert); therefore, open channel hydraulic theories were applied. Uniform flow conditions occurred throughout the length of the model culvert when it was placed at grade. Uniform flow occurs in open channels when (1) the depth, water area, velocity and discharge at every section of the channel reach are constant; and (2) the energy line, water surface and channel bottom are all parallel. For such conditions, Manning's equation can be used for computational purposes, given by (Chow 1959) as:

[4.1] $$Q = \frac{A R_h^{2/3} \sqrt{S}}{n}$$

where: Q is the discharge (m^3/s),

A is the flow area (m^2), and

n is a measure of boundary resistance referred to as Manning's n.

Uniform flow conditions did not occur for culvert placement depths of 0.1D and 0.2D due to backwater conditions throughout the length of the culvert, resulting in an M1 water surface profile.

4.1.2 Part-Full Flow through Culverts

A circular pipe with a uniform cross-section throughout its length, flowing partly full at both the inlet and outlet was used in this research study. The discharge was controlled at the outlet by the tailwater depth and was influenced by the slope, wall roughness and length of the culvert. The normal depth was greater than the critical depth for all tests; therefore, the culvert was operating with a mild slope. The culvert was flowing partly full in outlet control; therefore, the following energy balance equation applies:

$$[4.2] \quad LS + h_w + \frac{V_1^2}{2g} = t_w + H + \frac{V_2^2}{2g}$$

where: L is the length of culvert (m),

h_W is the headwater depth (m),

V_1 is the approach mean velocity (m/s),

t_w is the tailwater depth (m),

H is the total head loss given by $H_e + H_f + H_o$ (m),

H_e is the entrance head loss (m),

H_f is the friction head loss (m),

H_o is the outlet head loss (m), and

V_2 is the downstream mean velocity in the channel (m/s).

The head required to pass a given quantity of water through a culvert flowing in outlet control comprises of entrance loss, friction loss, and exit loss. The entrance loss depends upon the geometry of the inlet and is expressed as an entrance loss coefficient multiplied by the velocity head, or:

$$[4.3] \quad H_e = k_e \frac{V_b^2}{2g}$$

where: k_e is the entrance loss coefficient and

V_b is the mean velocity in the culvert barrel (m/s).

The friction loss is the energy required to overcome the resistance of the culvert barrel and is expressed by the following equation:

$$[4.4] \quad H_f = \left(\frac{2gn^2L}{R^{4/3}} \right) \frac{V_b{}^2}{2g}$$

The exit loss depends on the change in velocity at the outlet of the culvert, and is expressed as:

$$[4.5] \quad H_o = \left(y_b + \frac{V_b^2}{2g} \right) - \left(t_w + \frac{V_2^2}{2g} \right)$$

where y_b is the depth of water in the culvert barrel at the culvert outlet (m).

Consideration also needs to be given to the head recovery occurring at the culvert outlet. Head recovery is a term used to describe the amount of kinetic energy (or velocity head) of the flow in the culvert pipe that is converted to potential energy (or depth) in the downstream channel (Kells and Smith 1988). It is the difference between the tailwater depth and the depth of flow within the culvert barrel near the outlet. It is evidenced as a rise in the water surface immediately downstream of the culvert outlet. Kells and Smith (1988) have shown that a recovery coefficient, which is a non-dimensional quantification of the head recovery expressed in terms of the velocity head of the flow in the culvert, varies with the ratio of the cross-sectional area of the culvert to that of the downstream channel, given as

$$[4.6] \quad H_R = 2\left(A_r - A_r^2\right)\frac{V_b^2}{2g}$$

where: H_R is the head recovery (m), and

A_r is the ratio of the cross-sectional area of the culvert to that of the downstream channel.

4.1.3 Boundary Layer

The concept of the boundary layer is based on the fact that no slip occurs (i.e., the relative velocity is zero) at the interface between a moving fluid and a solid boundary. The region affected by boundary resistance is referred to as the boundary layer, which generally consists of a laminar sub-layer and a turbulent boundary layer. The velocity distribution in uniform flow will reach a definite pattern when the turbulent boundary layer is fully developed (Chow 1959). In turbulent flow, the velocity distribution can be shown to be approximately logarithmic, as given in Equation [2.1] and [2.2].

Bauer developed a correlation for turbulent boundary layer thickness on steep concrete overflow spillways, and it is given by Chow (1959) as

[4.7] $$\frac{\delta}{x_s} = \frac{0.024}{\left(x_s/k\right)^{0.13}}$$

where: δ is the boundary layer thickness (m),
x_s is distance from the spillway inlet (m), and
k is the boundary roughness height (m).

The boundary layer thickness for turbulent flow is also given by Schlichting (1968) as

[4.8] $$\delta = \frac{0.37x}{R_x^{0.2}}$$

where: x is the distance from the culvert inlet (m)
R_x is the Reynolds number using the streamwise distance as the characteristic length [Ux/υ],
U is the free stream velocity (m/s), and
υ is the kinematic viscosity of the fluid (m²/s).

When the surface is curved (e.g. a circular pipe), the boundary layer structure is more complex due to the existence of a pressure gradient. The pressure gradient in the boundary layer is caused by the variation in the free stream velocity. The characteristics of the entire flow are often highly dependent on the pressure gradient effects on the fluid within the boundary layer (Munson et al. 2002).

In this research program, the laminar boundary layer is very small due to roughness elements at the culvert entrance; thus, the turbulent boundary layer begins to develop at the culvert inlet. However, due to the complex flow structure caused by pressure gradients at the culvert boundary, the boundary thickness is very difficult to quantify.

4.1.4 Turbulence Intensity

The structure and characteristics of turbulence may vary from one flow situation to another. A uniform measurement scale of the level of turbulence is called the turbulence intensity, herein referred to as *TI*. *TI* is defined as the RMS of the velocity fluctuations at a particular location divided by the average of the velocity at the same location over the same time period. *TI* is given by (Munson et al. 2002).

[4.9] $$TI_u = \frac{RMS_{u'}}{\bar{u}}$$

[4.10] $$TI_v = \frac{RMS_{v'}}{\bar{v}}$$

[4.11] $$TI_w = \frac{RMS_{w'}}{\bar{w}}$$

where: TI_u, TI_v, TI_w are the turbulence intensities in the *x*-, *y*- and *z*- directions, respectively, at a point location,

$RMS_{u'}$, $RMS_{v'}$, $RMS_{w'}$ are the RMS of the velocity fluctuations in the *x*-, *y*- and *z*-directions, respectively, at the same point location (m/s), and

$\bar{u}$, $\bar{v}$, $\bar{w}$ are the time-averaged velocities in the *x*-, *y*- and *z*-directions, respectively, at the same location over the same time period (m/s).

The key part of the *TI* definition is use of the average velocity measured at a particular point location as the reference value. However, for this research program the mean velocity of the flow field during normal flow conditions was used instead because it is more appropriate in the context of practical culvert design. Further details regarding the decision to use the mean velocity of the flow field during normal flow conditions instead of the time-averaged velocity at a particular point are provided in Section 5.2.3.

A time period of 10 minutes was used to determine the average velocity and to provide determination of the RMS values.

4.2 Experimental Methodology and Data Analysis Procedures

4.2.1 Experimental Methodology

Experiments began with the culvert placed at grade with a slope of approximately 0.75%. The hydraulic results through the model culvert placed at grade allowed comparison to the results of a similar study by Ead et al. (2000) and to the results found through the model culvert placed at embedment depths of 0.1 and 0.2 times the culvert diameter (0.1*D* and 0.2*D*, respectively). Once measurements were taken for discharges of 50 L/s, 70 L/s and 90 L/s, and the model results were deemed acceptable, the model culvert was reinstalled to represent a culvert embedded to a depth of 0.1*D* (i.e., a depth of 0.05 m). The culvert was surveyed to ensure the slope was maintained at approximately 0.75%. The elevation of the model riprap was re-graded to match the elevation of the invert for a distance of one times the culvert diameter upstream and three times the culvert diameter downstream. Further upstream and downstream, the elevation of the model riprap remained at the original streambed level. Similarly, once measurements were taken for all three discharges, the model culvert was reinstalled to represent a culvert embedded to a depth of 0.2*D* (i.e., a depth of 0.1 m). Again, a survey was done to ensure the culvert slope of approximately 0.75% was maintained, and the model riprap was re-graded in the same manner as described above.

To summarize, the experiments included three placement configurations and three discharges. Therefore, the research program included nine combinations of culvert placement and discharge, as outlined in Table 4.1.

For each combination of placement and discharge, the following data were collected along the length of the culvert, as shown in Figure 4.1:

- Velocity distributions within a cross-section of the flow (i.e., within the *y-z* plane);
- Vertical velocity profiles along the centerline of the culvert; and
- Flow depths along the centerline of the culvert.

Table 4.1 Combination of culvert placements and discharges.

Culvert Placement	Discharge (L/s)
At grade	50
At grade	70
At grade	90
Embedment of 0.1*D*	50
Embedment of 0.1*D*	70
Embedment of 0.1*D*	90
Embedment of 0.2*D*	50
Embedment of 0.2*D*	70
Embedment of 0.2*D*	90

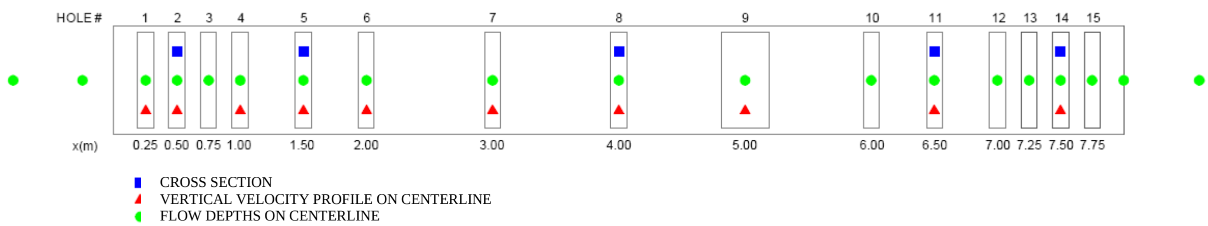

Figure 4.1 Schematic illustration of the locations of data collection.

The culvert tailwater depth was set by adjusting the tailgate. For tests with the culvert positioned at grade, the tailwater depth was set to produce normal depth within the culvert. Normal depth was calculated using Manning's equation (Equation 4.1) and the known discharge value, a Manning's n of 0.024 (as described in Appendix A), the surveyed culvert slope, and the known culvert diameter of 0.5 m. For the tests with the culvert placed at an embedment depth of 0.1*D*, the water depth within the culvert at the outlet end was set 0.1*D* (i.e., 0.05 m) above normal depth (i.e., to the same tailwater level as for the at-grade installation). Similarly, for the tests with the culvert placed at an embedment of 0.2*D*, the water depth was set to 0.1 m above normal depth. As such, a backwater condition existed through the culvert for the embedment mode of operation.

4.2.2 Data Collection Procedures

Velocity measurements in the *y*-*z* plane were collected at five locations along the length of the culvert, specifically at *x*-locations of 0.5 m, 1.5 m, 4.0 m, 6.5 m and 7.5 m for each combination of culvert placement and discharge. These locations correspond to Holes 2, 8, 5, 11 and 14, respectively. The locations were chosen to represent the inlet conditions, developed flow conditions and outlet conditions. Details of each cross-sectional flow measurements are given in Table 4.2.

Table 4.2 Details of the cross-sectional flow velocity measurements.

Culvert Placement	Discharge (L/s)	Hole No.	Location Along *x*-axis (m)	Culvert Slope (m/m)	Flow Depth at Culvert Outlet (m)
At grade	50	2	0.5	0.0072	0.184
At grade	50	5	1.5	0.0072	0.184
At grade	50	8	4.0	0.0072	0.184
At grade	50	11	6.5	0.0072	0.184
At grade	50	14	7.5	0.0072	0.184
At grade	70	2	0.5	0.0072	0.221
At grade	70	5	1.5	0.0072	0.221
At grade	70	8	4.0	0.0072	0.221
At grade	70	11	6.5	0.0072	0.221
At grade	70	14	7.5	0.0072	0.221
At grade	90	2	0.5	0.0072	0.256
At grade	90	5	1.5	0.0072	0.256
At grade	90	8	4.0	0.0072	0.256
At grade	90	11	6.5	0.0072	0.256
At grade	90	14	7.5	0.0072	0.256
0.1*D*	50	2	0.5	0.0075	0.231
0.1*D*	50	5	1.5	0.0075	0.231
0.1*D*	50	8	4.0	0.0075	0.231
0.1*D*	50	11	6.5	0.0075	0.231
0.1*D*	50	14	7.5	0.0075	0.231

Table 4.2 is continued on the next page.

Table 4.2 (cont'd) Details of the cross-sectional flow velocity measurements.

Culvert Placement	Discharge (L/s)	Hole No.	Location Along *x*-axis (m)	Culvert Slope (m/m)	Flow Depth at Culvert Outlet (m)
0.1*D*	70	2	0.5	0.0075	0.268
0.1*D*	70	5	1.5	0.0075	0.268
0.1*D*	70	8	4.0	0.0075	0.268
0.1*D*	70	11	6.5	0.0075	0.268
0.1*D*	70	14	7.5	0.0075	0.268
0.1*D*	90	2	0.5	0.0075	0.302
0.1*D*	90	5	1.5	0.0075	0.302
0.1*D*	90	8	4.0	0.0075	0.302
0.1*D*	90	11	6.5	0.0075	0.302
0.1*D*	90	14	7.5	0.0075	0.302
0.2*D*	50	2	0.5	0.0076	0.282
0.2*D*	50	5	1.5	0.0076	0.282
0.2*D*	50	8	4.0	0.0076	0.282
0.2*D*	50	11	6.5	0.0076	0.282
0.2*D*	50	14	7.5	0.0076	0.282
0.2*D*	70	2	0.5	0.0076	0.319
0.2*D*	70	5	1.5	0.0076	0.319
0.2*D*	70	8	4.0	0.0076	0.319
0.2*D*	70	11	6.5	0.0076	0.319
0.2*D*	70	14	7.5	0.0076	0.319
0.2*D*	90	2	0.5	0.0076	0.353
0.2*D*	90	5	1.5	0.0076	0.353
0.2*D*	90	8	4.0	0.0076	0.353
0.2*D*	90	11	6.5	0.0076	0.353
0.2*D*	90	14	7.5	0.0076	0.353

For each cross-section, the velocity was measured at approximately 40 to 50 point locations, represented by a *y-z* coordinate. The ADV probe was positioned using the ADV traverse system. A tape measure was used to ensure that the ADV apparatus was positioned centrally above the culvert, and as a check, the ADV was manually rotated through the cross-section before the pump was turned on. The flow depth along the centerline of the culvert was also measured at each cross-section by taking the difference between the point gauge measurement at the culvert bed on the top of a culvert corrugation and the point gauge measurement at the water surface.

All velocity measurements within a flow cross-section were measured continuously to avoid any changes in discharge or water temperature. In other words, the pump was not shut off and turned back on during a cross-section measurement. During all velocity measurements, the ADV traverse system and the real-time data being collected were carefully observed for any problems, such as poor quality data resulting from the ADV measuring too close to the culvert boundary.

For each combination of culvert embedment and discharge, vertical velocity profiles were collected at 10 locations along the length of the culvert, as shown in Figure 4.1. Five of the locations were measured in conjunction with the cross-section measurements at Holes 2, 8, 5, 11 and 14. The other five locations were collected at Holes 1, 4, 6, 7, and 9, which correspond, respectively, to *x*-locations of 0.25 m, 1.0 m, 2.0 m, 3.0 m, and 5.0 m. At each location along the length of the culvert, approximately seven to 12 point velocity measurements were made along the vertical axis (i.e., *z*-axis). The ADV was positioned using the ADV traverse system.

Flow depths were measured at 18 locations along the length of the culvert for each combination of culvert embedment and discharge, as shown in Figure 4.1. Flow depths were measured at each culvert access hole as well as upstream and downstream of the culvert. For each measurement, the exact location along the length of the culvert (i.e., the *x*-location) was determined using a tape measure glued along the length of the flume. Water depth was determined by taking the different between the point gauge measurement at the culvert bed, on the top of a culvert corrugation, and the point gauge measurement at the water surface.

4.2.3 Processing the Velocity Data

For each point location, the ADV output approximately 15,000 velocity samples (i.e., sampling rate of 25 Hz over a 10 minute interval). Each output sample included a signal-to-noise ratio (SNR), a correlation coefficient (CORR), and *x*-, *y*- and *z*-direction velocities relative to the probe orientation, referred to herein as *u*, *v* and *w*, respectively. The output data were collected using HorizonADV Windows-based software provided with the Sontek ADV probe.

Post-processing included filtering the data, transforming the coordinates from the probe coordinate system to the culvert coordinate system, and providing statistical summaries. Post-processing was done using a Windows-based viewing and post-processing utility called WinADV. WinADV was developed by Tony Wahl, a Hydraulic Engineer for the U.S. Bureau of Reclamation's Water Resources Research Laboratory, and it is freely distributed. WinADV can read the probe configuration and velocity data directly from a HorizonADV file without modifying the raw data (Wahl 2000).

Filtering was required because the ADV collected data regardless of conditions required to produce a reliable sample. The SNR and the CORR were used to filter bad samples out of the data files. Ideally, CORR values should be between 70% and 100%, while SNR values should be at least 15 when sampling at 25 Hz (Sontek 2005). Therefore, each output velocity sample was filtered using the following criteria:

- The average SNR had to be greater than 15; and
- The average CORR had to be greater than 70.

The velocity data were also filtered based on two spike-removal algorithms originally developed by Goring and Nikora (2002) and modified by Wahl (2000) for implementation into WinADV. The spike-removal is based on the concept that there should be a physical upper limit to the change in flow velocity (i.e., the acceleration) that can occur in a flow, and any measurements that indicate higher accelerations should be excluded from the analysis (Wahl 2000).

A coordinate transformation was required because the velocity values in the raw data files were relative to the probe orientation, and for this study, the probe rotated within the y-z plane to access locations off the culvert centerline. Therefore, the y- and z-direction velocities in the raw data files did not represent the actual v and w within the model culvert. However, the probe orientation was such that the x-direction velocity measured by the probe was the correct v within the model culvert. WinADV was used for the coordinate transformations.

Once the filtering and coordinate transformation were complete, a statistical summary of the point location data were transformed from 15,000 raw velocity samples into a time-averaged velocity in each direction and root-mean-square (RMS) of the velocity fluctuations in each direction. The time-averaged velocity in the *x*-, *y*- and *z*-directions are denoted with an overbar as $\overline{u}$, $\overline{v}$, and $\overline{w}$. The fluctuating part of the velocity is the time-varying portion that differs from the average value and is referred to as *u'*, *v'* and *w'* for the *x*-, *y*- and *z*-direction velocity fluctuations, respectively. The RMS of the velocity fluctuations in the *x*-, *y*- and *z*-directions are referred to as $RMS_{u'}$, $RMS_{v'}$ and $RMS_{w'}$, respectively.

Each statistical summary was assigned a coordinate with respect to the culvert coordinate system. The *y*- and *z*-coordinates (i.e., lateral and vertical) were calculated using trigonometry and the following:

- Known angle of rotation given by the ADV traversing system;
- Known location of the ADV on the automated slider given by the ADV traversing system;
- Length of the ADV probe which was 56.5 cm from the top of the ADV probe to the point in which the measurement was taken;
- Culvert diameter which was 50 cm; and
- Constant distance of 29.5 cm above the culvert at which the ADV was pivoting.

Figure 4.2 provides a schematic diagram of the lengths and angles used to determine the *y*- and *z*-coordinates. The dimension 'b' in the diagram was found by adding the known length of the ADV with the know distance that the ADV travelled on the automated slider. Sine and cosine functions were then used to calculate y and *z*. The *x*-coordinate (i.e., the distance along the culvert barrel from the inlet) was determined by recording the location along the length of the flume.

To summarize, after several processing steps, the 15,000 output velocity samples for a particular point in space were transformed into $\overline{u}$, $\overline{v}$, $\overline{w}$, $RMS_{u'}$, $RMS_{v'}$ and $RMS_{w'}$ at a particular *x*, *y*, *z* location (model coordinates).

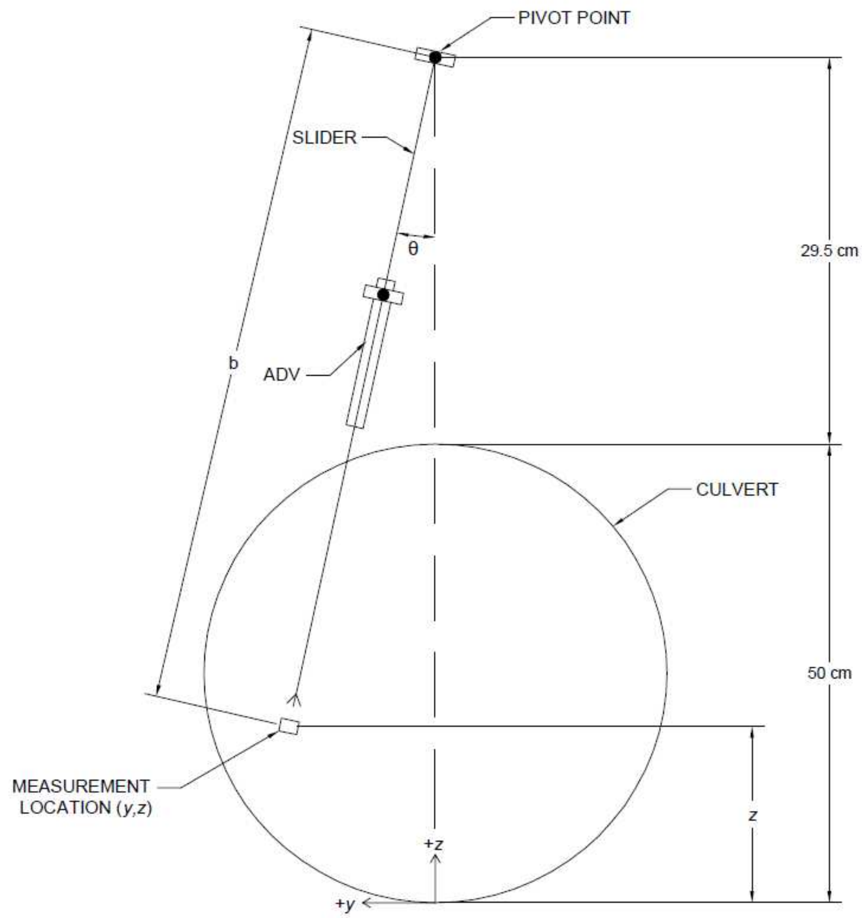

Figure 4.2 Schematic illustration of lengths and angles used to determine coordinates, looking downstream.

CHAPTER 5

PRESENTATION, ANALYSIS AND DISCUSSION OF RESULTS

5.1 Embedded Culverts vs. At-Grade Culverts

5.1.1 Water Surface Profiles

Throughout this research program only part-full flow conditions were studied. Thus, a free surface existed throughout the length of the culvert for all tests. Normal depth and critical depth were calculated for each discharge using the culvert slope of 0.75% and the culvert diameter of 0.5 m. The normal depths were greater than the critical depths, as shown in Table 5.1; therefore, the flow was subcritical and the channel was classified as having a mild slope.

Table 5.1 Computed normal and critical depths.

Discharge (L/s)	Culvert Slope (%)	Normal Depth (m)	Critical Depth (m)
50	0.75	0.18	0.15
70	0.75	0.22	0.18
90	0.75	0.25	0.20

For tests in which the culvert was placed at grade, uniform flow conditions were made to occur throughout the length of the culvert by adjusting the downstream tailgate so that normal depth existed at the downstream end of the culvert. However, uniform flow conditions did not occur for culvert placement depths of 0.1D and 0.2D due to backwater conditions throughout the length of the culvert (i.e., the tailgate was adjusted to create flow depths at the culvert outlet to be greater than normal depth). These backwater conditions created an M1 water surface profile within the culvert. The extent of the M1 profile throughout the length of the culvert was found by assessing the flow depths along the length of the culvert and by using an analytical approach.

Flow depths were measured along the length of the culvert for each combination of discharge and embedment. Figures 5.1 and 5.2 show the variation in flow depth along the culvert centerline throughout its length. For ease of comparison, the data have been shown twice. Figure 5.1 shows three plots, with each plot representing a culvert placement, while Figure 5.2 shows each plot representing a different discharge. Appendix D provides a table containing the values represented in the series of graphs.

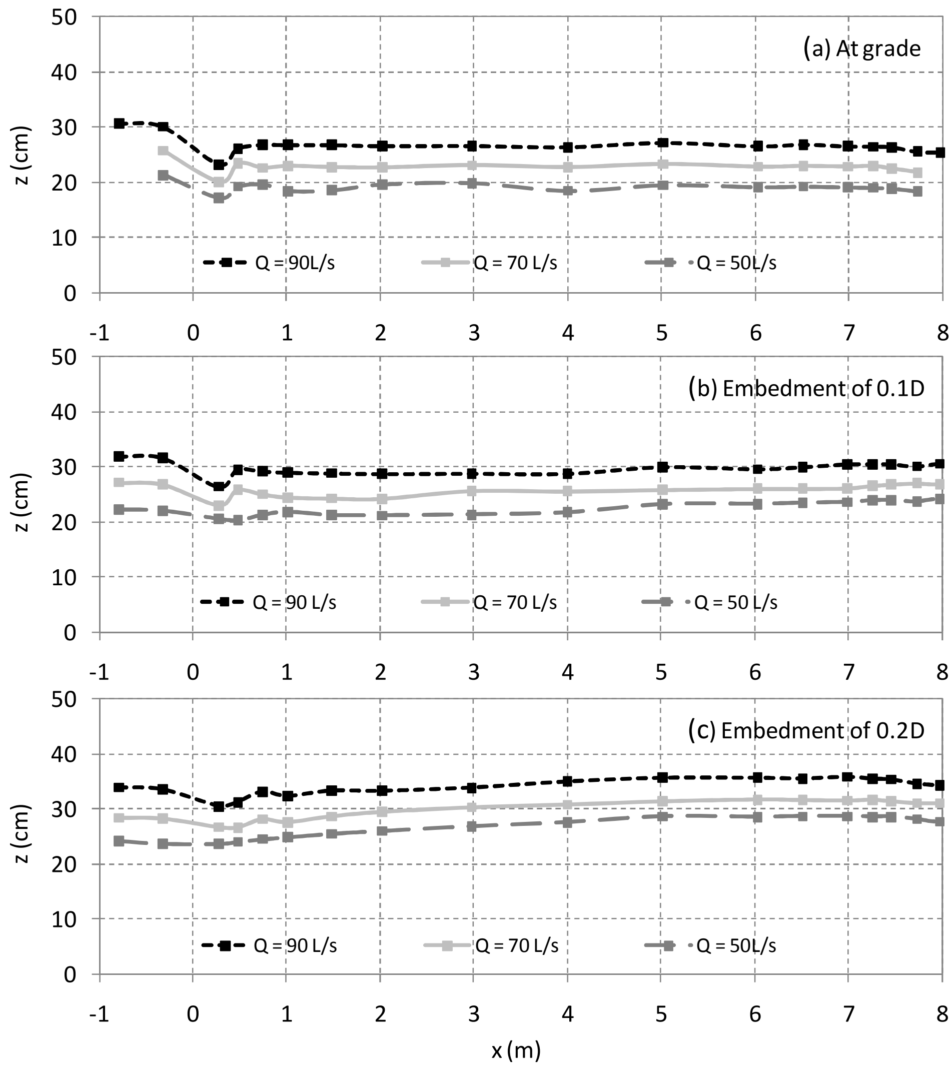

Figure 5.1 Measured water surface profiles along the culvert centerline for discharges of 50 L/s, 70 L/s and 90 L/s for the culvert placed (a) at grade, (b) at an embedment of 0.1*D* and (c) at an embedment of 0.2*D*.

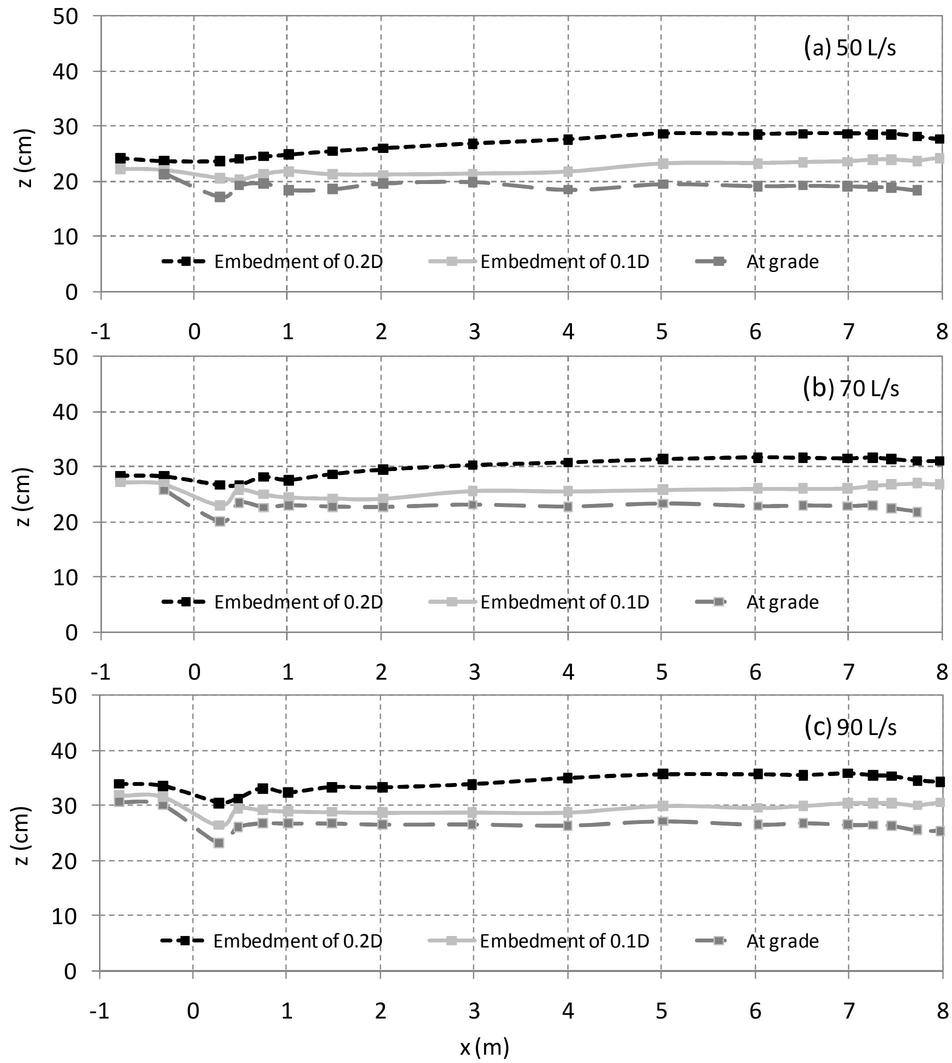

Figure 5.2 Measured water surface profiles along the culvert centerline for the culvert placed at grade, an embedment of 0.1*D* and an embedment of 0.2*D* for discharges of (a) 50 L/s, (b) 70 L/s and (c) 90 L/s.

All profiles shown in Figures 5.1 and 5.2 experience a hydraulic drop at the entrance, which is due to flow contraction, followed by a rise. The rise is due to the flow expansion. Once outside of the entrance region, the water level for the at-grade condition appears parallel to the culvert invert, with the depth of flow being approximately equal to normal depth. For the culvert placed at embedments of 0.*1D* and 0.2*D*, the water levels are greater throughout the length of the culvert than the water levels when the culvert was placed at grade. Because the water levels during embedments of 0.1*D* and 0.2*D* do not collapse back to the water levels measured during normal flow conditions at any point along the length of the culvert, it can be concluded that, for conditions tested in this study, an M1 water surface profile exists throughout the length of the culvert when the culvert is embedded. The lengths of the M1 profiles for each combination of embedment and discharge were also computed analytically using the direct step method. The results of the calculated water surface profiles are shown in Figures 5.3.

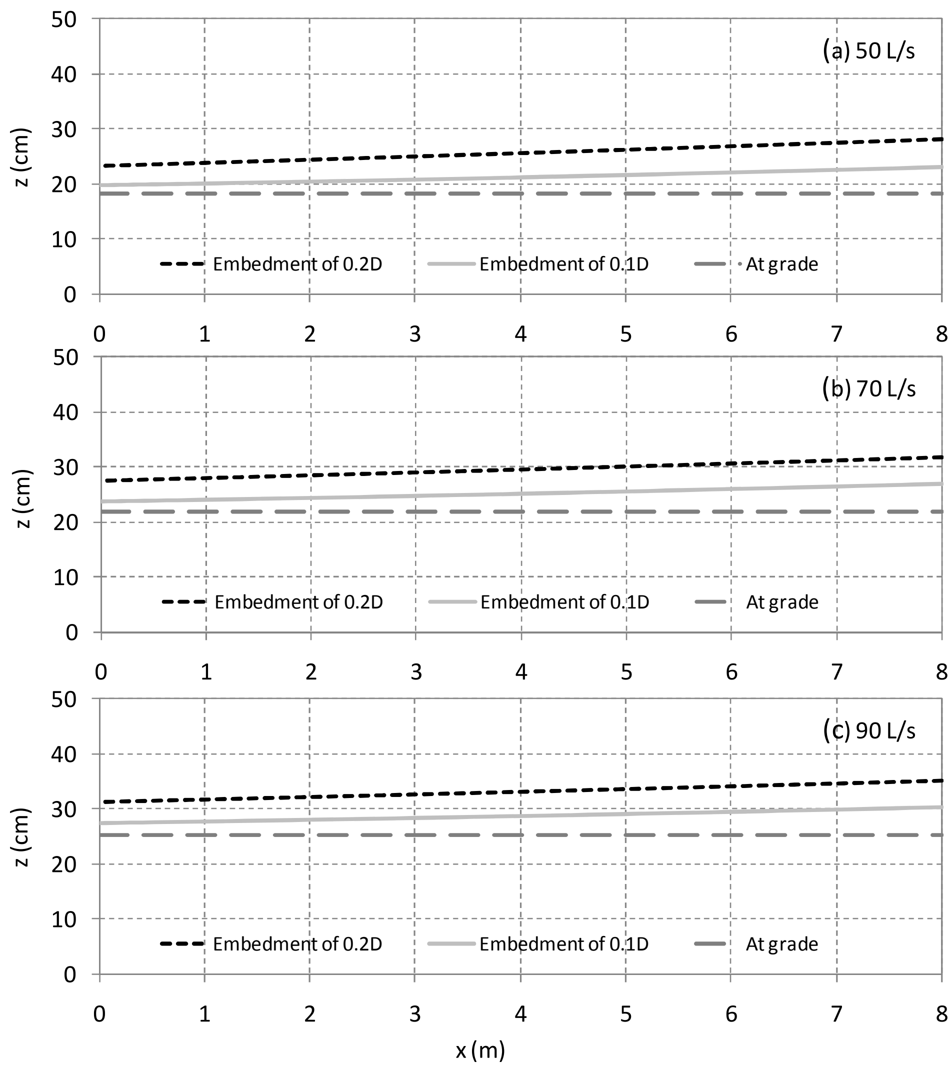

Figure 5.3 Analytical water surface profiles using the direct step method for the culvert placed at-grade, an embedment of 0.*1D* and an embedment of 0.2*D* for discharges of (a) 50 L/s, (b) 70 L/s and (c) 90 L/s.

Figure 5.3 shows that for all three discharges, the water levels throughout the length of the culvert for the embedment conditions are greater than the water levels during at-grade conditions (i.e. normal depth). This means that an M1 profiles extends throughout the length of the culvert for each of the embedment test conditions. These results are consistent with the measured water surface profiles. Figure 5.4 shows both the analytical and measured results on one graph for each discharge condition. The measured results are consistent with the analytical results, within a centimeter or two.

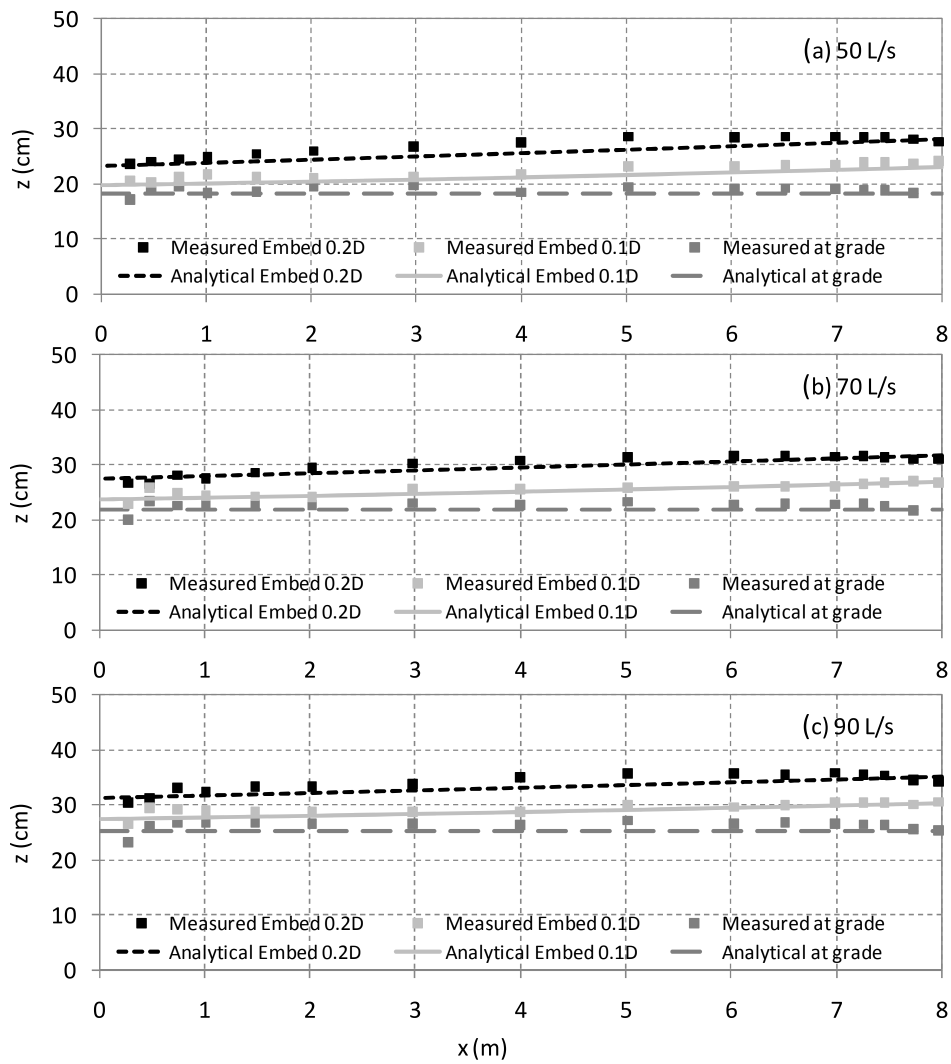

Figure 5.4 Analytical and measured water surface profiles for the culvert placed at-grade, an embedment of 0.1*D* and an embedment of 0.2*D* for discharges of (a) 50 L/s, (b) 70 L/s and (c) 90 L/s.

Eliminating the dimensions of the data allows for easier comparisons. The measured water surface profiles are plotted non-dimensionally in Figure 5.5. The depth of flow was normalized using the normal depth of flow for the at-grade condition while the longitudinal position was normalized using the culvert diameter.

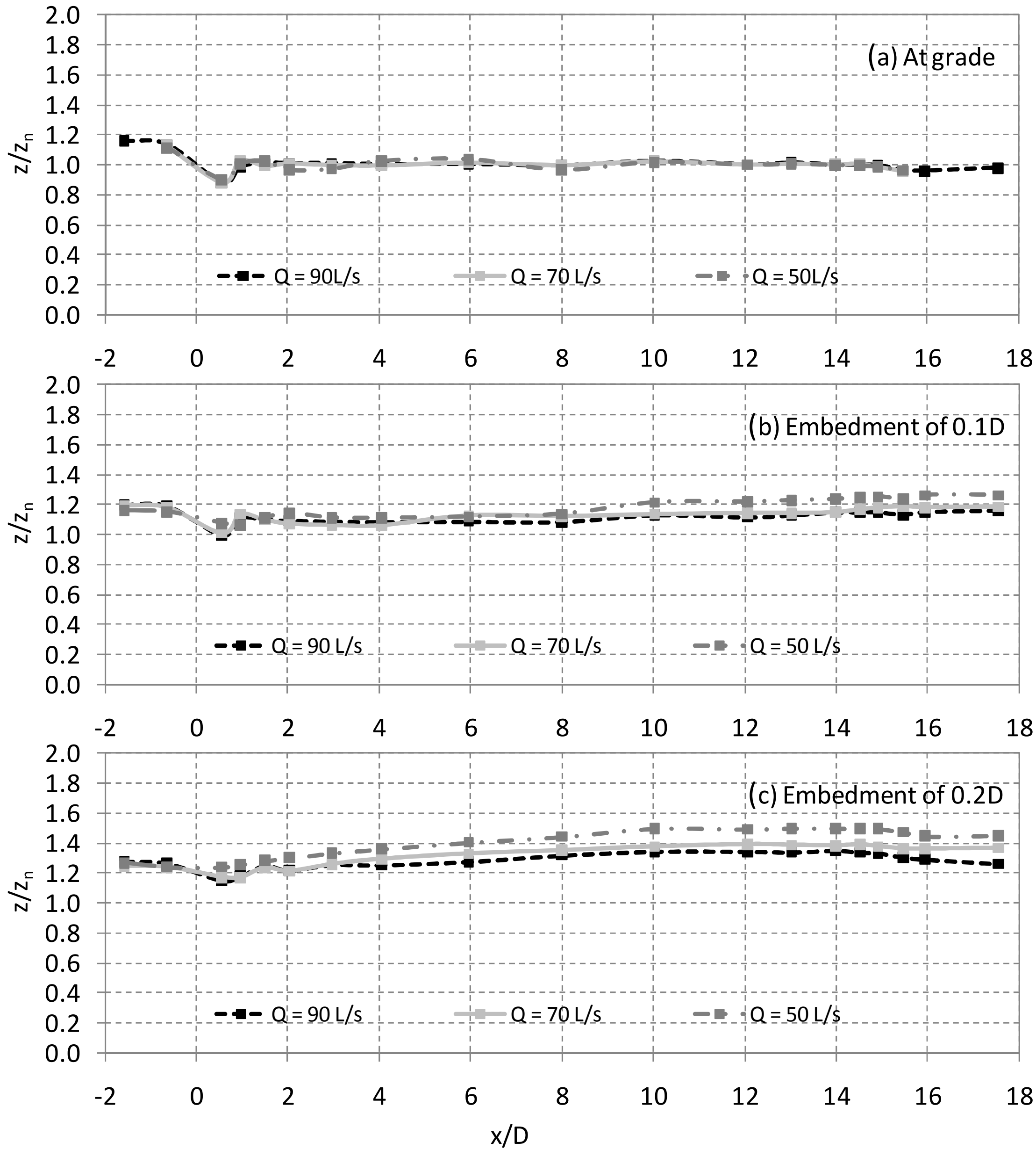

Figure 5.5 Non-dimensionalized measured water surface profiles along the culvert centerline for the culvert placed (a) at grade, (b) at an embedment of 0.1*D* and (c) at an embedment of 0.2*D*.

Figure 5.5(a) shows that the water surface profiles collapse into one line at approximately $z/z_n = 1.0$, as expected for the at-grade condition. For the culvert placed at an embedment of 0.1*D*, the profiles occur at values slightly above $z/z_n = 1.0$. The values range from approximately 1.1 to 1.2, depending on the location along the length of the culvert. For the culvert placed at an embedment of 0.2*D*, the profiles occur at z/z_n values ranging from approximately 1.1 to 1.5, again depending on the location along the culvert. In other words, flow depths were approximately 1.1 to 1.5 times the normal depth when the culvert was embedded due to the M1 water surface profile occurring throughout the length of the culvert.

From these water surface profiles, it can be concluded that embedding a culvert creates an M1 water surface profile. In this research study, the profile extended the entire length of the culvert. However, for other culvert configurations, such as a longer pipe or a different culvert slope, the extent of the M1 profile will be different. It may or may not occur throughout the entire length of the culvert. The water depth may reach normal depth somewhere within the culvert barrel, creating conditions similar to an at-grade culvert installation. In these situations, the M1 profile may help the fish enter the culvert, but may not necessarily improve hydraulic conditions throughout the entire culvert length. However, a reduction in the length of high velocity is a benefit to fish passage. As the results show, an analytical approach can be used to determine if the M1 water surface profile extends throughout the entire length of the culvert or not.

5.1.2 Vertical Velocity Profiles

The significance of an M1 water surface profile throughout the length of the culvert is that, for a given discharge, the flow depths are greater than those for normal flow conditions. This, in turn, results in lower mean velocities, which relates directly to the fish passage criterion that states that the mean cross-sectional velocity in a culvert should not be greater than the capability of the weakest swimming fish. For this research study, vertical velocity profiles were taken at multiple locations along the length of the culvert. A comparison is then made between the velocities measured when the culvert was placed at grade to the velocities measured when the culvert was embedded.

Vertical velocity profiles were collected on the central axis of the flow at 10 locations along the length of the culvert. These profiles, along with the water surface profiles, are shown in Figures 5.6 to 5.8, with each figure representing a different discharge.

For ease of interpreting the plots, the scale on the x-axis and the y-axis display a maximum of 8 m and 50 cm, respectively, that represent the culvert outlet and crown. The velocity profiles are shown at the location where they were measured. For example, the vertical velocity profile measured at 4.0 m from the culvert inlet is shown at $x = 4.0$ m, as given by the bottom point in the profile. As shown by the scales on Figures 5.6(a), 5.7(a) and 5.8(a), a distance of 0.5 m on the x-axis represents a streamwise velocity of 125 cm/s. Each profile is drawn to the same scale so that comparisons can be made. The water surface profiles are shown to assist in better visualizing the flow through the culverts.

It is important to note that the ADV is incapable of measuring within 5 cm of the water surface; therefore, there are no data for the top portion of each profile, as evident from the plots. For some measurements, the ADV was incapable of measuring at distances even more than 5 cm from the water surface due to water bubbles interfering with the ADV signal. For these cases, measurements were taken, but the ADV's sample SNR or CORR did not meet the specified criteria and the measurements were filtered out.

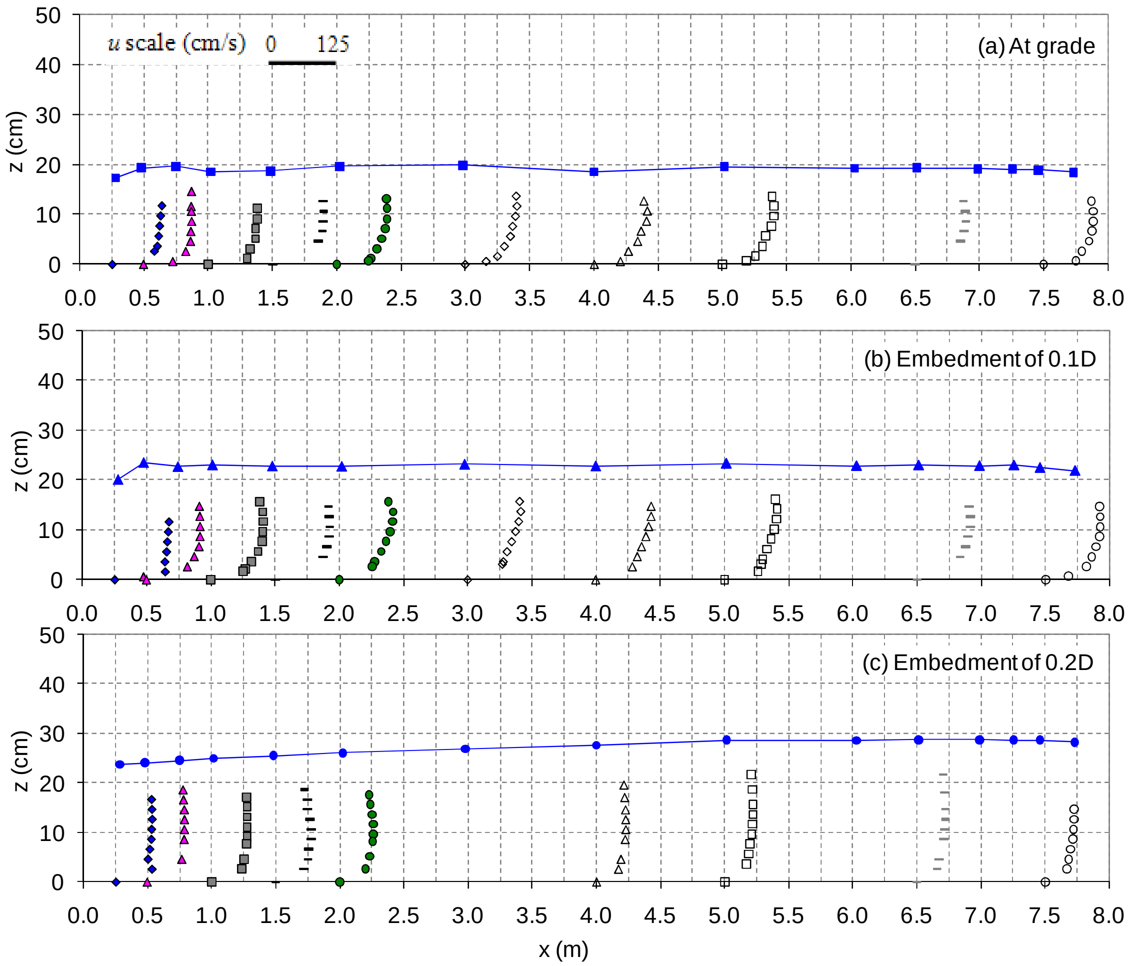

Figure 5.6 Water surface profiles and centerline vertical velocity profiles for a discharge of 50 L/s for the culvert placed (a) at grade, (b) at an embedment of 0.1*D* and (c) at an embedment of 0.2*D*.

Figure 5.6 shows the vertical velocity profiles collected when the discharge was set to 50 L/s. Figure 5.6(c) does not include data at x = 3.0 m because an error occurred during data collection. When comparing the velocity profiles among culvert placements, the figures show that the velocity decreases with embedment depth. For example, when looking at x = 5.0 m, the velocity profile in Figure 5.6(a) shows the profile has a maximum velocity of approximately 100 cm/s. However, the velocity profile in Figure 5.6(b) has a maximum velocity of approximately 80 cm/s, while the profile in Figure 5.6(c) has a maximum velocity of approximately 60 cm/s.

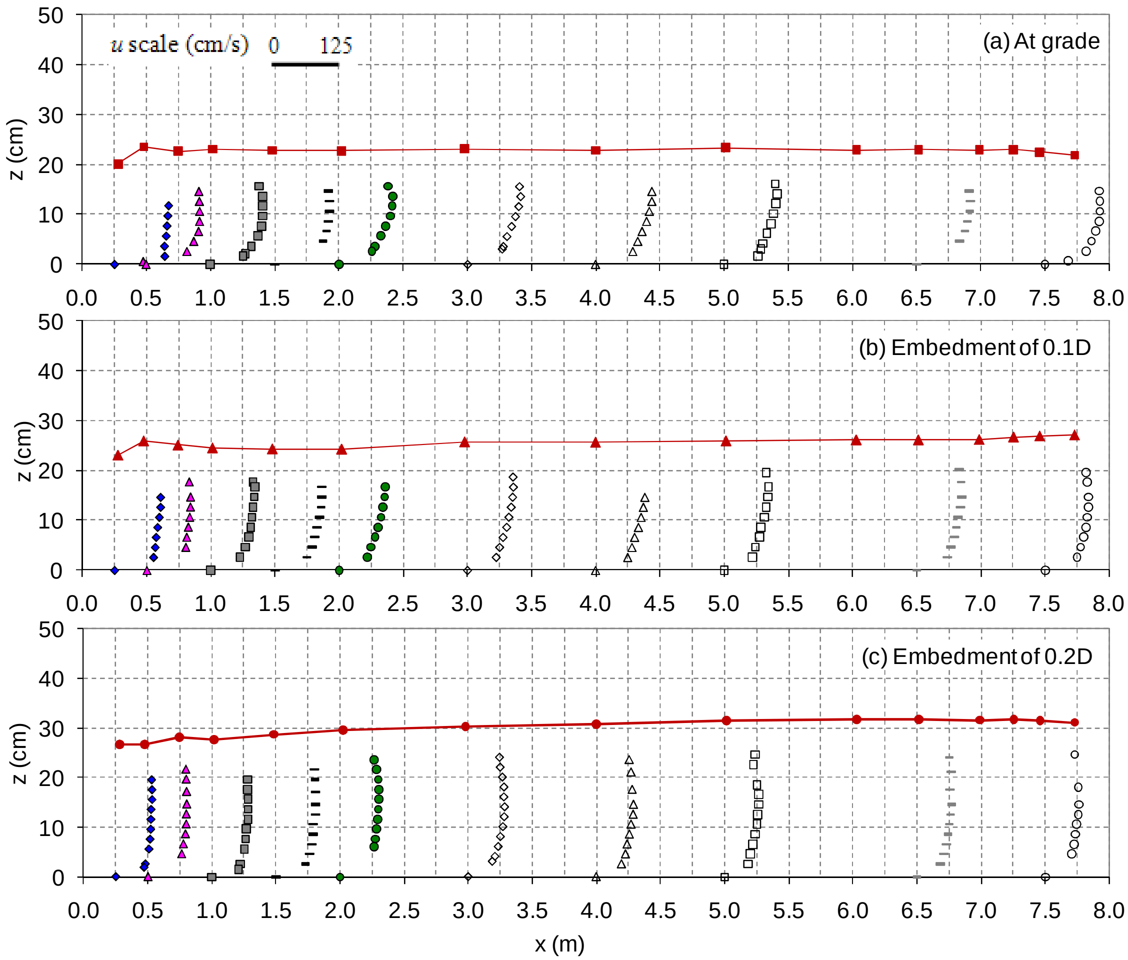

Figure 5.7 Water surface profiles and centerline vertical velocity profiles for a discharge of 70 L/s for the culvert placed (a) at grade, (b) at an embedment of 0.1*D* and (c) at an embedment of 0.2*D*.

A decrease in velocity with embedment can also be seen in Figures 5.7 and 5.8, which show profiles measured when the discharge was set to 70 L/s and 90 L/s, respectively. The idea that velocities decrease with embedment is important when designing culverts for fish passage. For example, if a culvert design does not meet fish passage criteria, instead of increasing the culvert size, which increases culvert costs, one may only need to increase culvert embedment. However, it is important to note that if the M1 water surface profile does not extend through the entire culvert length, then fish passage may still be compromised.

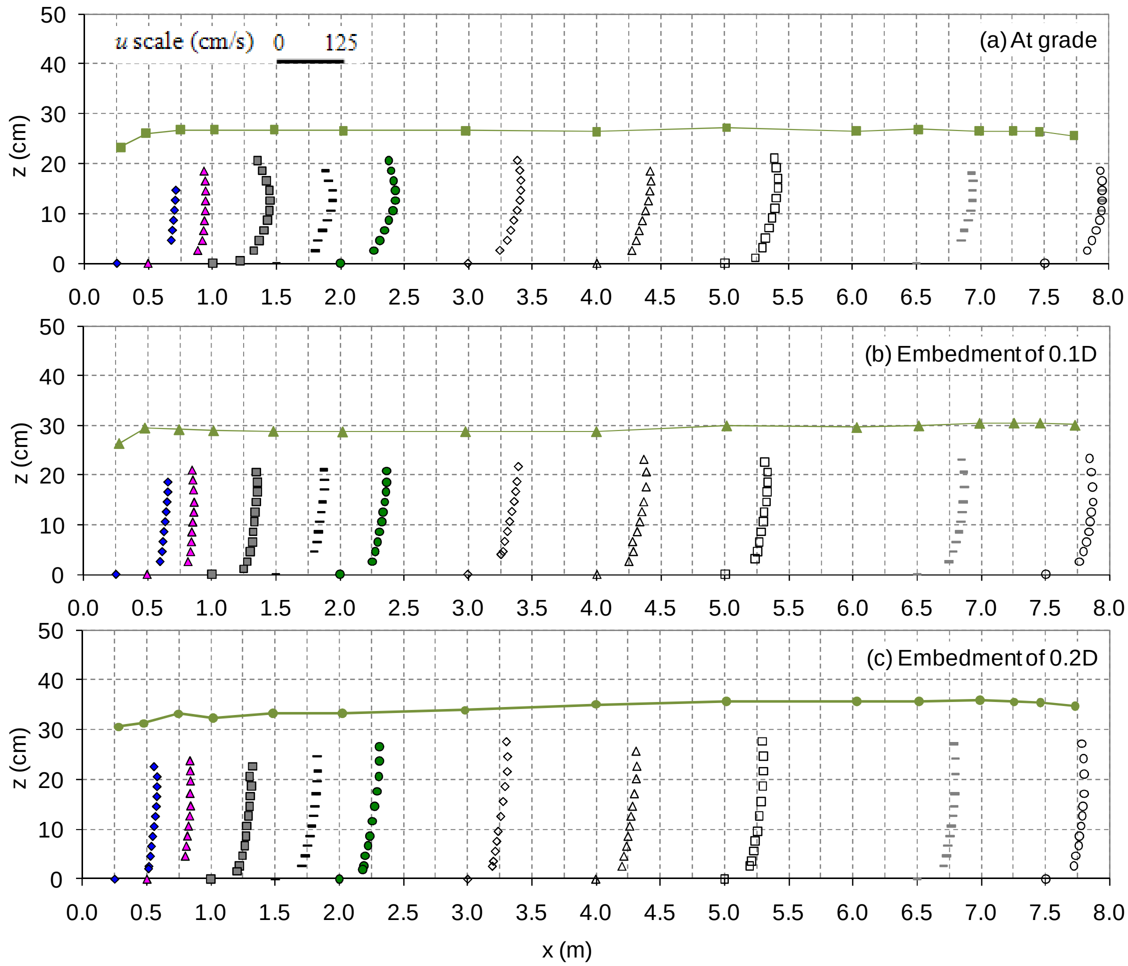

Figure 5.8 Water surface profiles and centerline vertical velocity profiles for a discharge of 90 L/s for the culvert placed (a) at grade, (b) at an embedment of 0.1*D* and (c) at an embedment of 0.2*D*.

The flow development along the length of the culvert is influenced by the boundary layer thickness. In theory, the boundary layer will continue to grow in thickness until it reaches the water surface, and at that point, the pattern of velocity distribution becomes stable and the flow is considered to be fully developed (Chow 1959). Although Figures 5.6 to 5.8 show the development of flow along the culvert, it is difficult to visually determine the boundary layer thickness. Therefore, the Schlichting method for solving the theoretical boundary layer thickness for turbulent flow (as given in Equation 4.8) was applied to the flow measurements taken when the culvert was placed at grade. This boundary layer assessment was only applied to at-grade conditions because with an M1 water surface profile, a stable velocity profiles with position will not be reached due to increasing flow depth in the flow direction.

The Schlichting equation is dependant on distance from culvert invert, free stream velocity and the kinematic viscosity of the fluid. The free stream velocity was estimated to be 100 cm/s, 105 cm/s and 110 cm/s for when the culvert discharge was set to 50 L/s, 70 L/s and 90 L/s. The kinematic viscosity of the fluid was 8.0×10^{-7} m²/s (Munson et al. 2002). Figure 5.9 shows the calculated boundary layer growth using the Schlichting equation with the previously presented vertical velocity profiles along the length of the culvert.

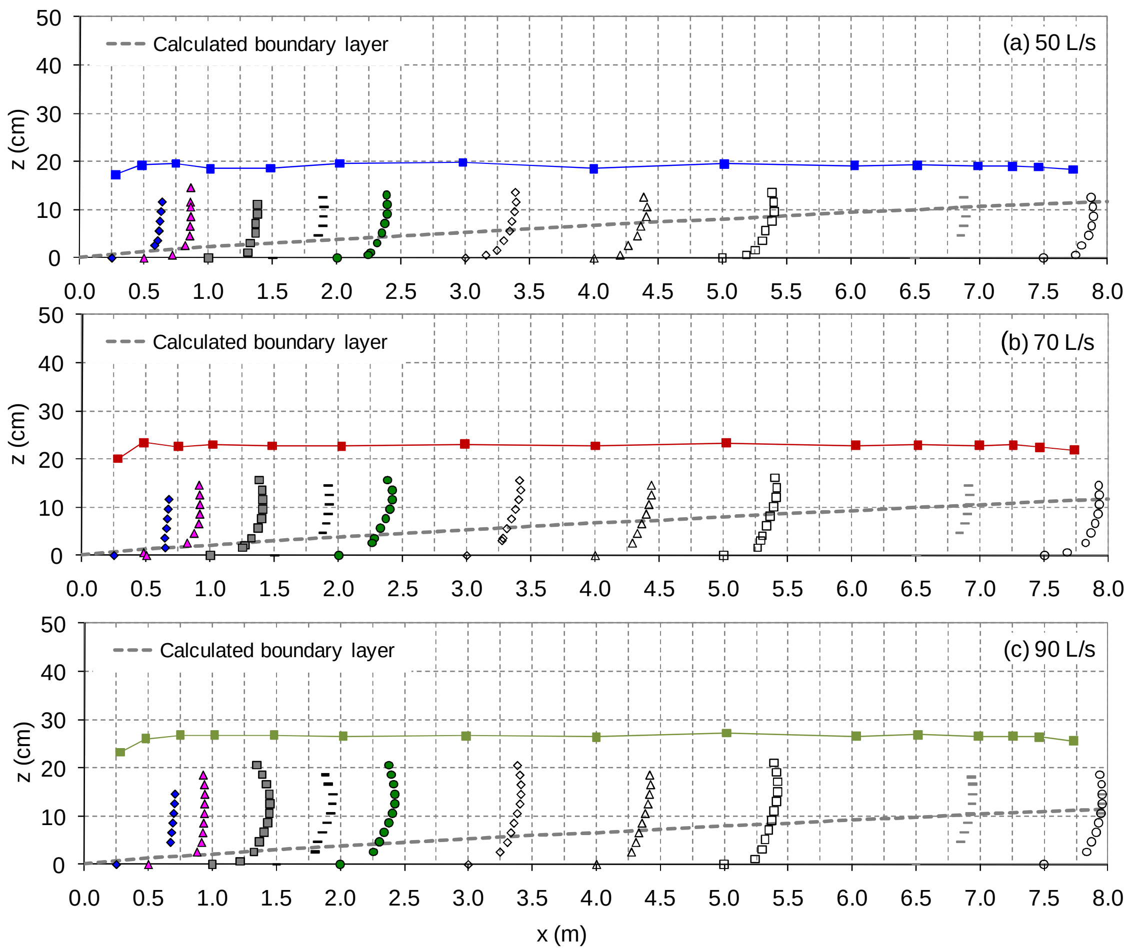

Figure 5.9 Water surface profiles, centerline vertical velocity profiles and boundary layer growth calculated using the Schlichting equation for the culvert placed at grade with discharges of (a) 50 L/s, (b) 70 L/s and (c) 90 L/s.

The results of the boundary layer thickness, using the Schlichting equation, indicate that the boundary layer thickness does not reach the water surface, which in theory, means that the flow is not fully developed along the length of the culvert. However, the Schlichting method was used strictly as an estimate of the boundary layer growth because when the surface is curved (e.g. a circular culvert, such as this application), the boundary layer structure is more complex due to the existence of a pressure gradient. The pressure gradient in the boundary layer is caused by the variation in the free stream velocity, and the characteristics of the entire flow are often highly dependent on the pressure gradient effects on the fluid within the boundary layer (Munson et al. 2002).

As said previously, the flow is considered fully developed when the velocity profiles become a stable pattern. Therefore, to further look at flow development along the length of the culvert for at-grade conditions, Figures 5.10(a), 5.11(a) and 5.12(a) show the centerline vertical velocity profiles measured at each location superimposed on each other. The idea is to visually examine the profiles to see if they become stable along the length of the culvert.

In order to compare vertical velocity profiles among embedment, each figure also includes the profiles measured at an embedment of 0.1*D* and 0.2*D*. However, profiles measured during embedment conditions are not expected to become stable with position along the culvert due to the M1 water surface profile (i.e., flow is not fully developed). Each figure represents a different discharge. Appendix E provides tables containing the values represented in this series of graphs.

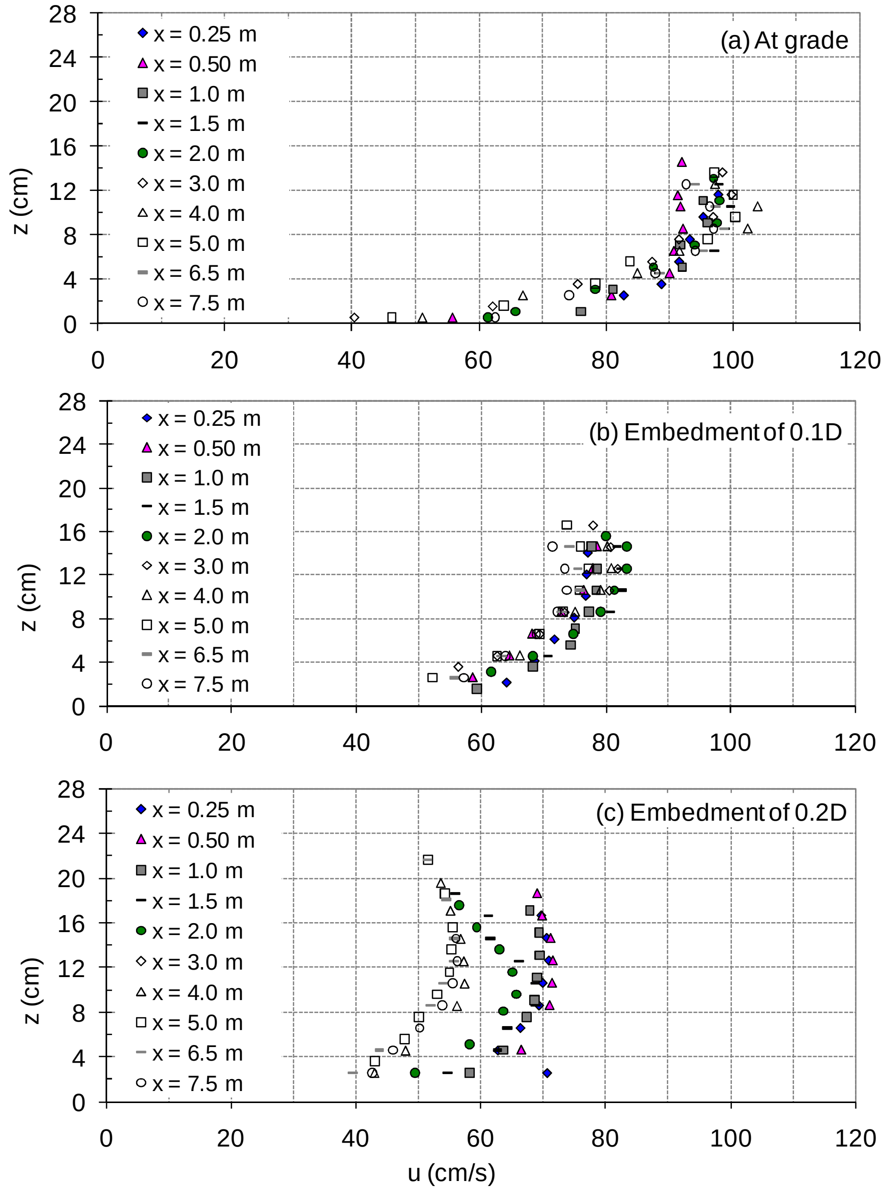

Figure 5.10 Centerline vertical velocity profiles for a discharge of 50 L/s for the culvert placed (a) at grade, (b) at an embedment of 0.1*D* and (c) at an embedment of 0.2*D*.

When looking at flow development along the culvert, Figure 5.10(a) shows a spread in maximum velocity from approximately 91 cm/s to 102 cm/s. It is difficult to see a collapse in the data to determine at what point along the length of the culvert that the flow becomes fully developed. As expected, the vertical velocity profiles do not collapse for embedments of 0.1*D* and 0.2*D*. For example, when looking at Figure 5.10(c), the spread shows that profiles measured near the culvert entrance have greater velocities than profiles measured near the culvert exit. The difference in velocities are expected due to the difference in flow depths caused by the M1 water surface profile (i.e., flow depth increases in the direction of flow).

When comparing profiles among embedment, Figure 5.10 shows that the maximum velocity decreases with embedment. For example, Figure 5.10(a) shows the maximum velocity to be approximately 97 cm/s during normal conditions, while Figure 5.10(b) shows the maximum velocity to be approximately 80 cm/s, resulting in a decrease of approximately 17% when embedding the culvert 0.1*D*. A further reduction of the maximum velocity to 70 cm/s occurs when the culvert is embedded 0.2*D*. This equates to a 28% decrease in velocity from normal conditions.

Figures 5.11 and 5.12, which are for discharges of 70 L/s and 90 L/s, respectively, show a similar trend when looking at flow development and differences among embedment. For example, when looking at flow development, Figures 5.11(a) and 5.12(a) show considerable spread in the velocity profiles making it difficult to determine where the flow may become fully developed. The spread in profiles also increases with discharge. During embedment conditions, the profiles do not collapse, as expected, and the spread in velocity profiles are generally greater when the culvert is placed at an embedment of 0.2*D* than those when the culvert at 0.1*D*. This difference in spread is due to the greater difference in flow depth caused by the M1 water surface profile.

When comparing profiles among embedment, Figures 5.11 and 5.12 show that the velocity decreases with embedment. With a discharge of 70 L/s, the maximum centerline vertical velocity during normal conditions is approximately 105 cm/s. The maximum for an embedment of 0.1*D* and 0.2*D* is approximately 90 cm/s and 75 cm/s, respectively, which is a decrease of approximately 14% and 28%, respectively, from normal flow conditions. With a discharge of 90 L/s, as shown in Figure 5.12, the maximum centerline vertical velocity during normal conditions is approximately 115 cm/s. The maximum for an embedment of 0.1*D* and 0.2*D* is approximately 100 cm/s and 85 cm/s, respectively, which is a decrease of approximately 13% and 26%, respectively, from normal flow conditions.

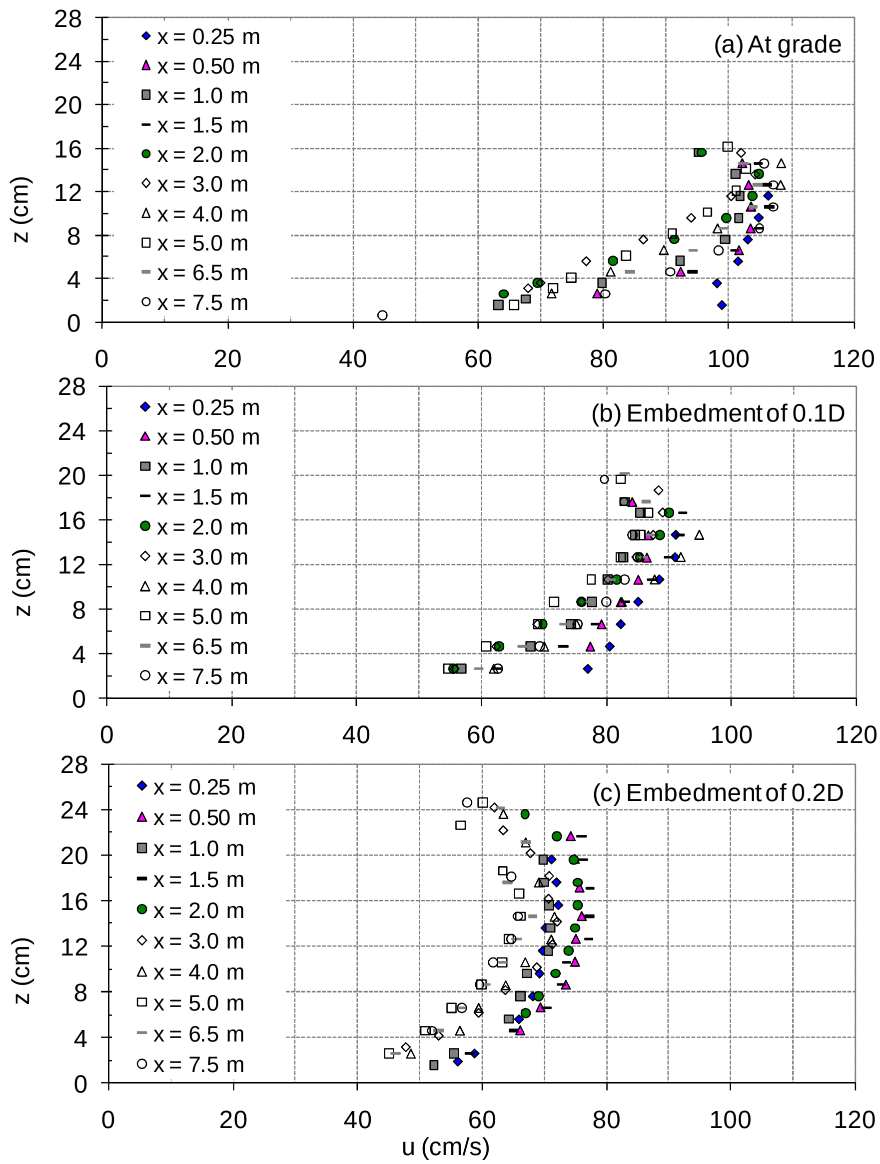

Figure 5.11 Centerline vertical velocity profiles for a discharge of 70 L/s for the culvert placed (a) at grade, (b) at an embedment of 0.1*D* and (c) at an embedment of 0.2*D*.

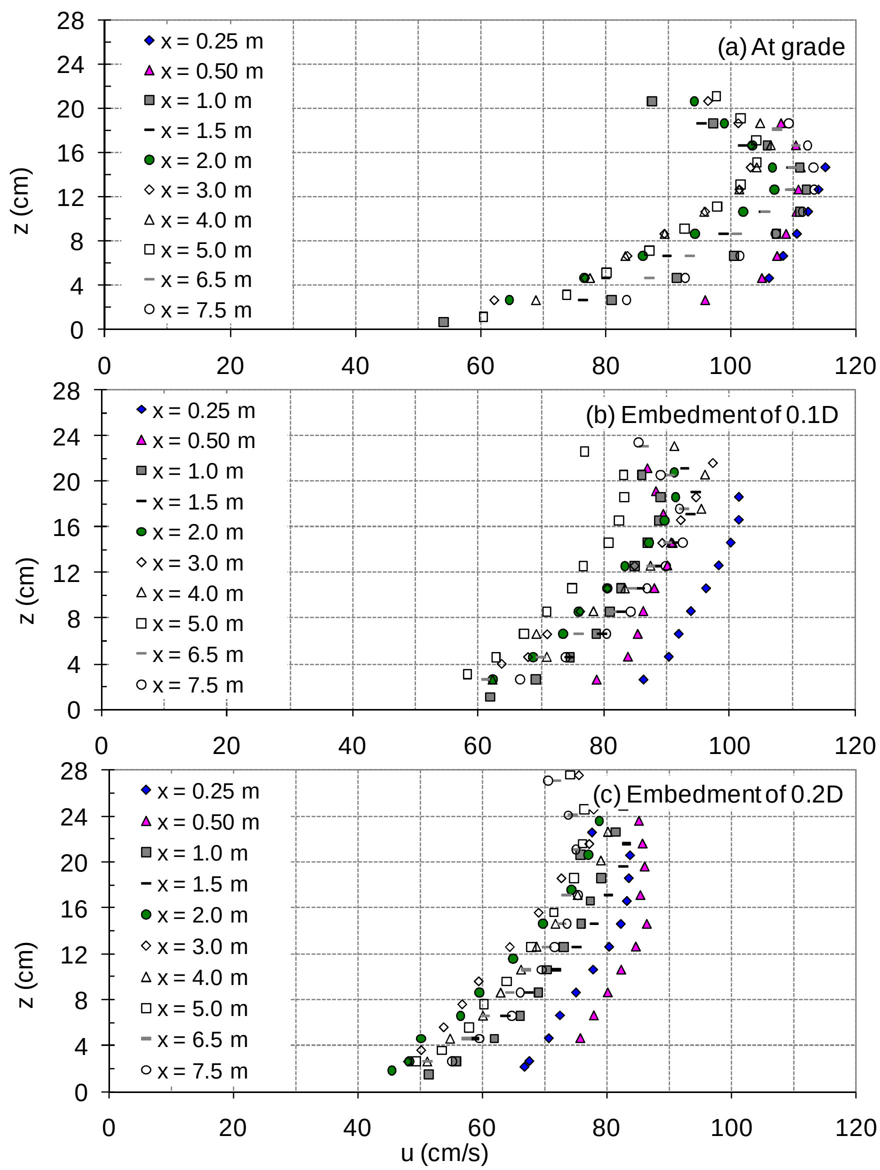

Figure 5.12 Centerline vertical velocity profiles for a discharge of 90 L/s for the culvert placed (a) at grade, (b) at an embedment of 0.1*D* and (c) at an embedment of 0.2*D*.

Because it was difficult to see a collapse in the data for the culvert placed at grade in Figures 5.10 to 5.12, the vertical velocity profiles were also non-dimensionalized to allow for easier comparisons. The depth was normalized using the maximum depth, while the streamwise velocity was normalized using the maximum streamwise velocity. Figure 5.13 shows all profiles along the length of the culvert, while Figure 5.14 shows only profiles from x = 3.0 m to the culvert outlet.

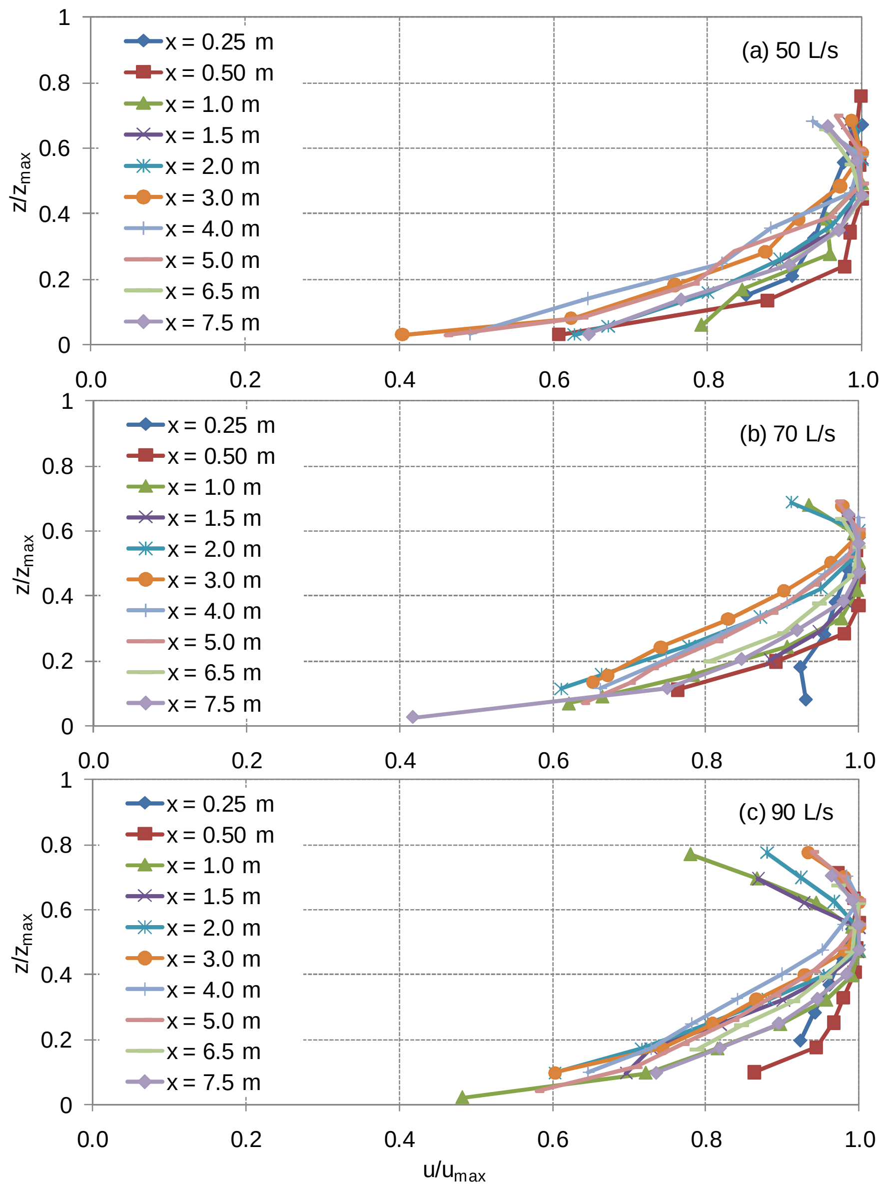

Figure 5.13 Centerline vertical velocity profiles along the entire culvert length non-dimensionalized by the maximum depth and the maximum velocity for the culvert placed at grade with discharges of (a) 50 L/s, (b) 70 L/s and (c) 90 L/s.

In Figure 5.13, there is spread among profiles, and it is difficult to see any collapse. However, when removing the profiles measured near the culvert inlet (i.e., x = 0.25 m, 0.50 m, 1.0 m, 1.5 m, 2.0 m), as shown in Figure 5.14, it appears that the profiles do not completely collapse, but show a similar pattern in shape. The spread in profiles appears to be consistent among discharge. For example, when looking at z/z_{max} = 0.4, the maximum spread among profiles for each discharge is approximately $0.1u_{max}$ (i.e, 0.9 to 1.0 on the *x*-axis). u_{max} was approximately 100 cm/s, 105 cm/s and 110 cm/s for discharges of 50 L/s, 70 L/s and 90 L/s; therefore the spread in velocity profiles was approximately 10 cm/s to 11 cm/s.

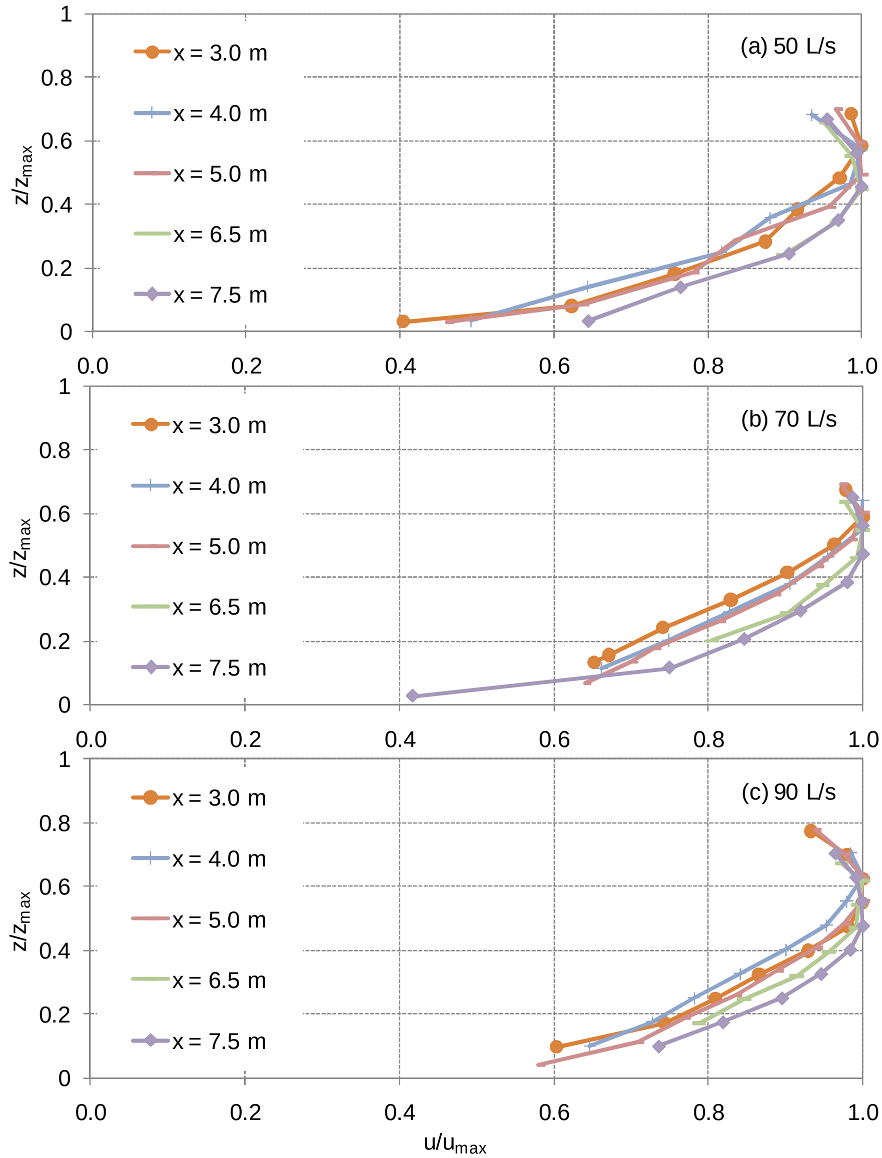

Figure 5.14 Centerline vertical velocity profiles from x = 3.0 m to the culvert outlet non-dimensionalized by the maximum depth and the maximum velocity for the culvert placed at grade with discharges of (a) 50 L/s, (b) 70 L/s and (c) 90 L/s.

Ead et al. (2000) performed a similar velocity profile analysis after measuring the centerline vertical velocity profiles in a 0.62 m diameter culvert was placed at grade with a slope of 0.55% and a discharge of 160 L/s. They concluded that the profiles were invariant when the spread was approximately 10 cm/s or less. For this research study, it is similarly concluded that the centerline vertical velocity profiles become invariant after the spread is approximately 10 cm/s. Hence, the flow is assumed to be fully developed after x = 3.0 m. Ead et al. (2000) found the flow to be fully developed after x = 1.0 m.

For comparisons among embedment, the centerline vertical velocity profiles were non-dimensionalized in a slightly different manner. The depth was similarly normalized using the maximum depth; however, the streamwise velocity was normalized using the mean velocity. Two different mean velocities were used such that Figure 5.15 uses the mean velocity of the flow during normal flow conditions (i.e., Q/A measured for the at-grade condition), while Figure 5.16 uses the mean velocity of the flow at a particular cross-section (i.e., Q/A for each particular cross-section). Only vertical velocity profiles at longitudinal locations of 4.0 m, 6.5 m and 7.5 m (i.e. fully developed flow region where full cross-sections were measured) were used so that the graphs did not become cluttered with data points.

Figure 5.15 shows that, for the conditions tested in this research study, the greater the embedment, the greater the decrease in velocity from normal flow conditions. For example, embedding the culvert 0.1D caused the maximum velocity to decrease from approximately from 1.3V_n to approximately 1.1V_n for all three discharges. Embedding the culvert 0.2D caused the maximum velocity to decrease further to approximately 0.8V_n to 0.9V_n. This analysis is sensitive to where on the M1 water surface profile the vertical velocity profile exists, since the flow depth is increasing in the direction of flow. However, this analysis may be useful from a practical perspective to understand the effect that embedment has on velocities within a culvert. However, it is important to understand these results are specific to the conditions studied in this research program and may not necessarily be applied to all culvert designs.

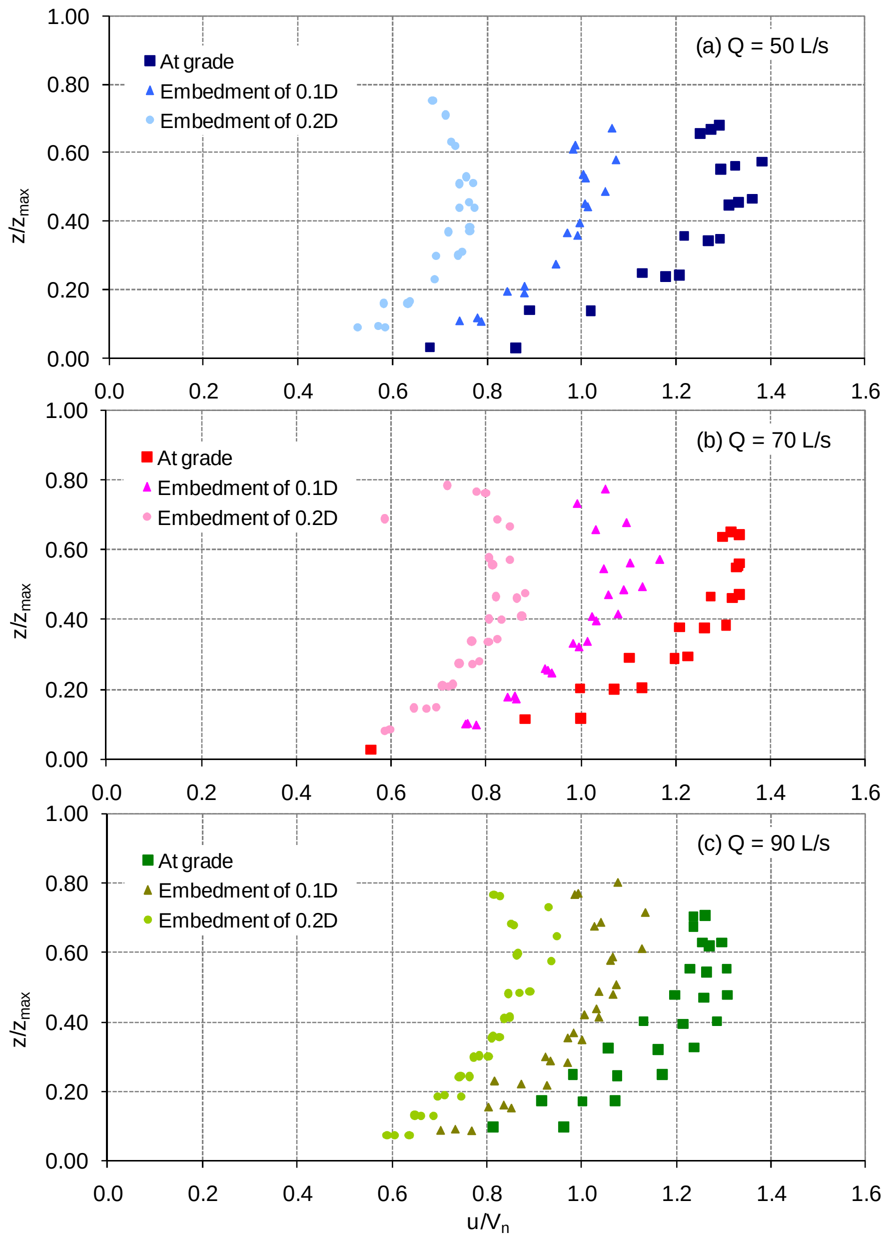

Figure 5.15 Centerline vertical velocity profiles at x = 4.0 m, 6.5 m and 7.5 m non-dimensionalized by the maximum depth and cross-sectional mean velocity of the flow for normal flow conditions for discharges of (a) 50 L/s, (b) 70 L/s and (c) 90 L/s.

Figure 5.16 shows the centerline vertical velocity profiles similar to Figure 5.15, except that the streamwise velocity is normalized using the mean velocity for each particular cross-section and embedment condition instead of the mean velocity during normal flow conditions. Figure 5.16 shows that the profiles collapse with the maximum velocity consistently around 1.3 times the mean velocity, whether the culvert is placed at grade or embedded.

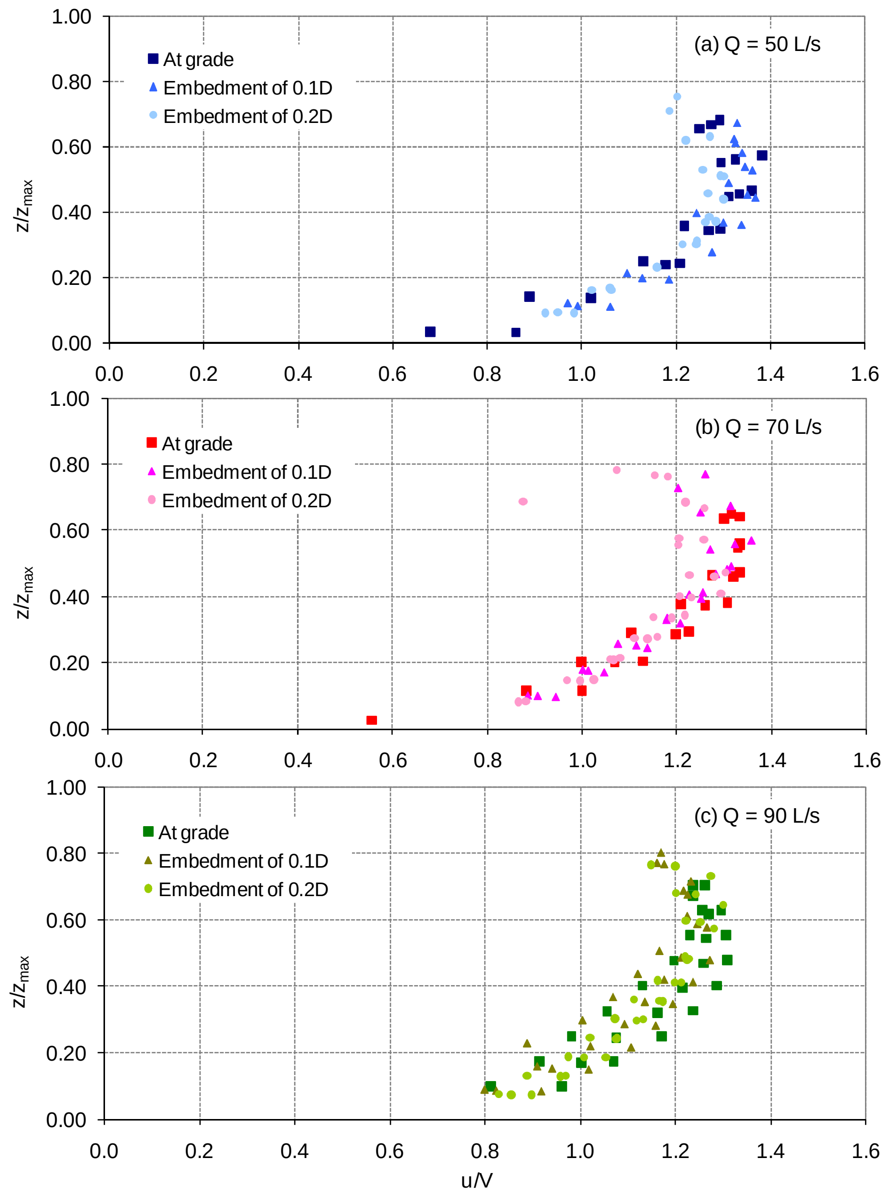

Figure 5.16 Centerline vertical velocity profiles at x = 4.0 m, 6.5 m and 7.5 m non-dimensionalized by the maximum depth and mean velocity at that particular cross-section for discharges of (a) 50 L/s, (b) 70 L/s and (c) 90 L/s.

Vertical velocity profiles can also be calculated analytically using the classic Prandtl-von Karman velocity distribution law for fully developed hydraulically rough flow regimes, as described by Equation 2.2. The equation requires variables such as the equivalent sand grain roughness height and the shear velocity. The height of the culvert corrugations was 0.013 m; therefore, an equivalent sand grain roughness height of 0.013 m was used in this analysis. The shear velocities for this research study were back-calculated out of Equation 2.2 using measured data. Determining the shear velocities was done by manipulating Equation 2.2 into the form:

$$[5.1] \quad u = 5.75u_*(\log z) + \left[u_*\left(-5.75\log k_s + 8.5\right)\right]$$

Equation 5.1 can be considered a linear relationship when u is plotted on the vertical axis and log z is plotted on the horizontal axis. Then $5.75u_*$ represents the slope and $[u_*(-5.75\log k_s+8.5)]$ represents the intercept.

For normal flow conditions measured in this research study (i.e. the culvert placed at grade), velocity profiles measured in the fully developed region were plotted in a semi-log form such that the streamwise velocity was along the vertical axis and the vertical distance from the invert was along the horizontal axis. The shear velocity at the central axis was determined from the slope of the plots, as shown in Figure 5.17. The shear velocities found for all test conducted with the culvert placed at grade were approximately 0.074 m/s. This method of determining the shear velocity was used by Ead et al. (2000) and Magura (2007). For example, Ead et al. (2000) found the shear velocity to be approximately 0.097 m/s when their model culvert with a diameter of 0.62 m was placed at grade with a slope of 0.55% and a discharge of 160 L/s.

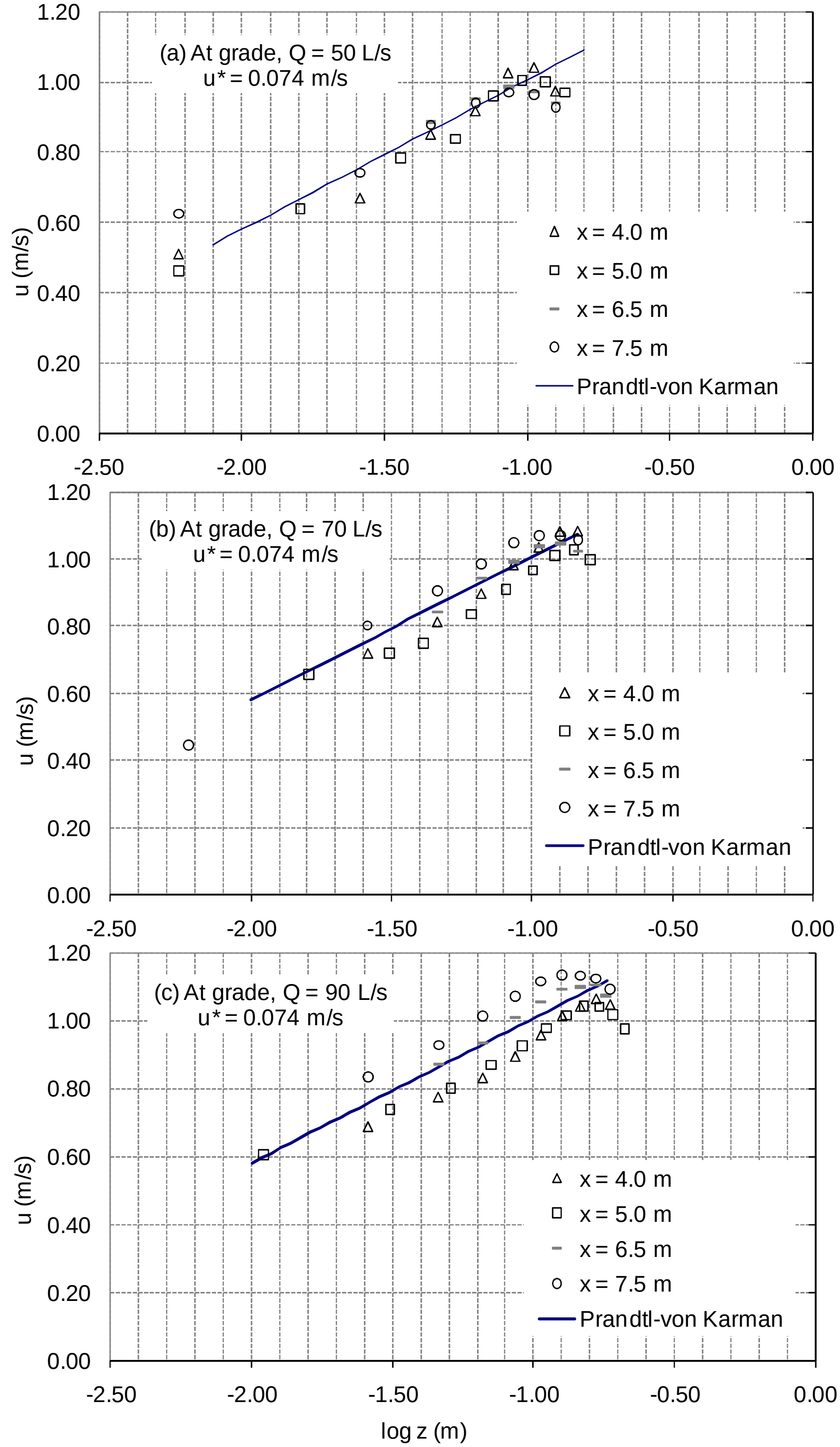

Figure 5.17 Semi-log form of vertical velocity profiles within the developed flow region for the culvert placed at-grade for discharges of (a) 50 L/s, (b) 70 L/s and (c) 90 L/s.

Although the Prandtl-von Karman velocity distribution law for hydraulically rough flow regimes is for fully developed flow regions, the shear velocity was also calculated using the method described above for the case in which the culvert was placed at an embedment of 0.1*D* and 0.2*D* (i.e., for conditions in which there was not fully developed flow). This analysis was done to find an approximate value of the shear velocity for use when calculating the Prandtl-von Karman vertical velocity profiles. The shear velocity found for each combination of culvert placement and discharge is shown in Table 5.2.

Table 5.2 Calculated shear velocity on centerline for each combination of culvert placement and discharge.

Culvert Placement	Discharge (L/s)	Shear Velocity (m/s)
At grade	50	0.074
At grade	70	0.074
At grade	90	0.074
0.1*D*	50	0.057
0.1*D*	70	0.060
0.1*D*	90	0.062
0.2*D*	50	0.040
0.2*D*	70	0.046
0.2*D*	90	0.049

Once the shear velocities were estimated, the vertical velocity profiles were calculated analytically using the Prandtl-von Karman equation for fully developed rough flow regimes (Equation 2.2). Figure 5.18 shows the calculated profiles along with measured non-dimensionalized centerline vertical velocity profiles. The measured profiles are similar to those presented in Figure 5.15, except that the flow depth is normalized using the culvert diameter of 0.5 m. The culvert diameter was used to provide a constant normalizing length. The maximum depth, for example, would not be constant throughout the conditions tested because of the M1 water surface profile existing for conditions in which the culvert was placed at an embedment of 0.1*D* and 0.2*D*.

Figure 5.18 shows that the calculated velocity profiles are similar to the measured profile, which is expected since the calculated profiles were found using the measured shear velocities. In other words, the Prandtl-von Karman curves were created using measured data to essentially predict the measured data. From a practical perspective, it may be difficult to analytically calculate the vertical velocity profiles because the shear velocity is likely unknown.

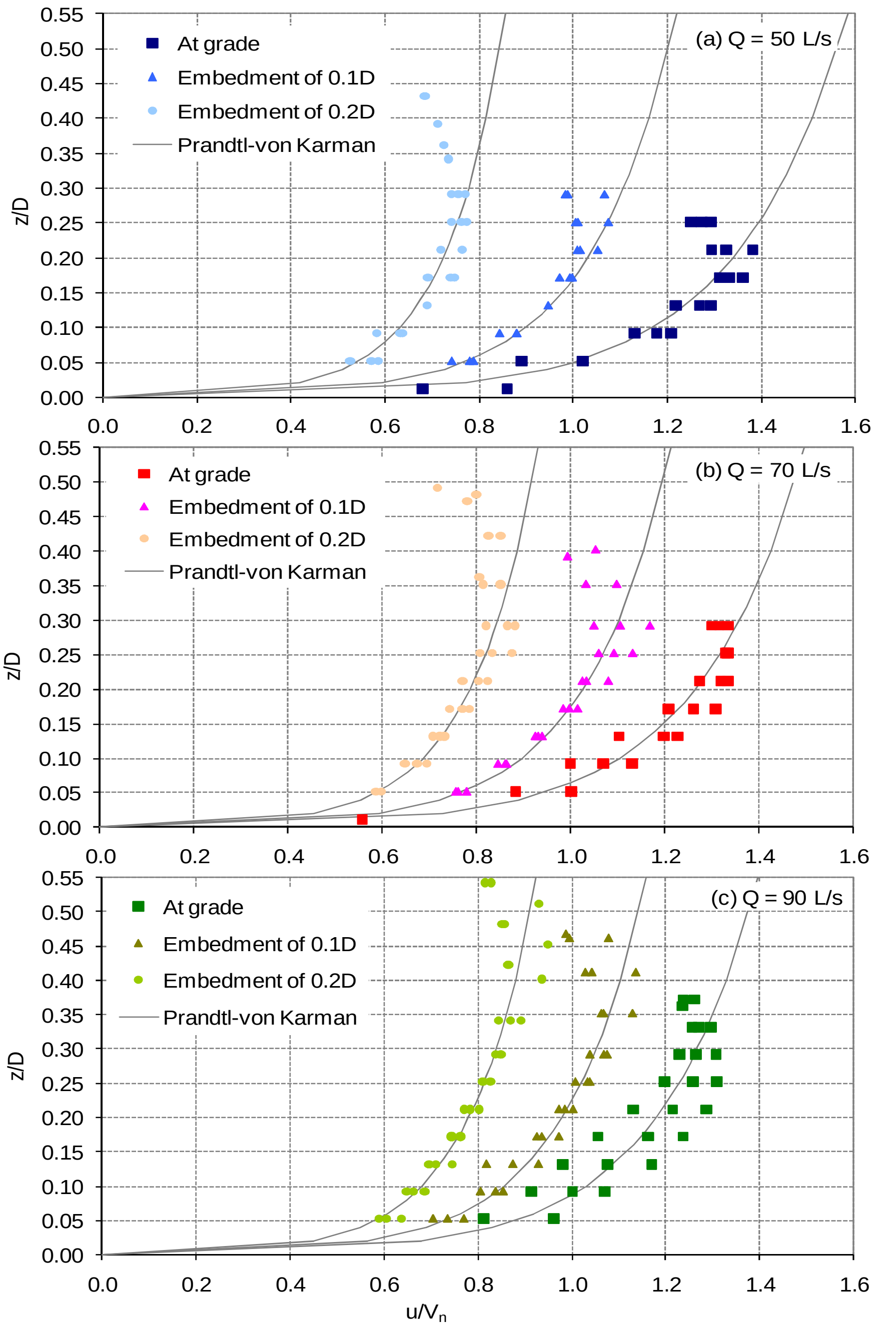

Figure 5.18 Centerline vertical velocity profiles and Prandtl-von Karman equation for rough flow regime, non-dimensionalized using the mean velocity of the flow field for the at-grade condition, for the developed flow region for discharges of (a) 50 L/s, (b) 70 L/s and (c) 90 L/s.

5.1.3 Head Loss

If a M1 water surface profile exists throughout the entire length of a culvert, the flow depths will be greater than normal flow conditions. For a certain discharge, the increased flow depths will result in reduced velocities. As a result of reduced velocities throughout the length of the culvert, the total head loss is reduced. Specifically, a decrease in entrance head loss can impact fish passage because of reduced flow acceleration. At the culvert entrance (or fish exit), a contraction zone occurs for water entering the culvert from the inlet pool. An eddy forms in the space surrounding the contracted jet inside the pipe, as shown in Figure 5.19. This eddy absorbs energy from the flow causing entrance head loss. The second cause of entrance head loss is the expansion zone just downstream of the contraction and eddy zone. The amount of head loss is generally estimated by multiplying a coefficient by the velocity head within the culvert barrel.

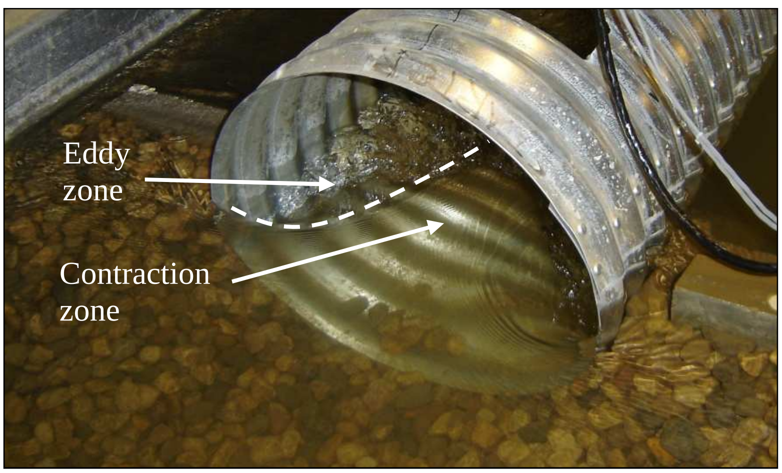

Figure 5.19 Photograph showing an eddy forming in the space surrounding the contracted jet inside the pipe. The expansion zone is not visible in this photograph.

A comparison of head loss occurring between the culvert placed at grade and embedded can be made using the energy balance equation for partly-full culverts in outlet control given in Equation 4.2. For each combination of culvert discharge and embedment, all but one component of the equation is known: the total head loss. Therefore, the total head was calculated using the measured flow depths and discharge, the surveyed culvert slope, and the known culvert length. The headwater and tailwater depths were measured. The velocities in the barrel and downstream of the outlet were found by dividing the measured discharge by the calculated flow area.

The three components of the total head loss (entrance loss, friction loss and exit loss) were also solved. Friction loss and exit loss were solved using Equations 4.4 and 4.5. The entrance head loss was then calculated by subtracting the friction and exit loss from the total head loss. Figure 5.20 shows each component stacked on each other for all combinations of culvert discharge and embedment.

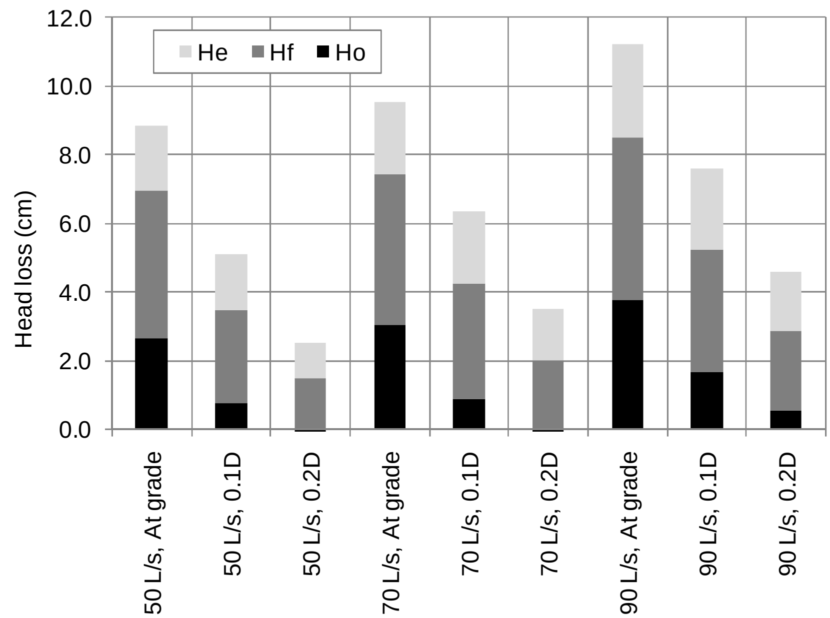

Figure 5.20 Head loss for each combination of discharge and embedment based on measurements of discharge and flow area.

Figure 5.20 shows that the total head loss decreases with embedment. For example, for a discharge of 50 L/s, the total head loss decreases from approximately 8.5 cm during normal flow conditions to 5.0 cm and 2.5 cm for the culvert placed at an embedment of 0.1*D* and 0.2*D*, respectively. Although each component of head loss decreased with embedment, the exit head loss decreased the most. During discharges of 50 L/s and 70 L/s, the exit loss became almost zero (i.e., not even visible in Figure 5.20) when the culvert was placed at an embedment of 0.2*D*. The exit head loss depends on the change in flow depth and velocity between the culvert barrel and the downstream tailwater. During backwater conditions (i.e., M1 water surface profile), the difference in velocity and flow depth between the culvert barrel and downstream tailwater is small; therefore, it seems reasonable that the exit head loss becomes very small. Total head loss also increased with discharge. These results mean that the culvert exit (or fish entrance) of embedded culverts have reduced velocities and less of a water elevation change compared to culverts installed at grade. A reduction in velocity will help fish enter the culvert.

As stated previously, the entrance head loss was calculated by subtracting the friction and exit loss from the total head loss. In practical situations, the entrance head loss is typically calculated using an entrance loss coefficient, as shown in Equation 4.3. Figure 5.21 presents the entrance loss coefficients for each combination of discharge and embedment that were found by dividing the entrance head loss by the velocity head in the culvert. The entrance loss coefficients range from 0.75 to 0.97, which are comparable to the published value of 0.9 for culverts projecting from fill (CSPI 2002).

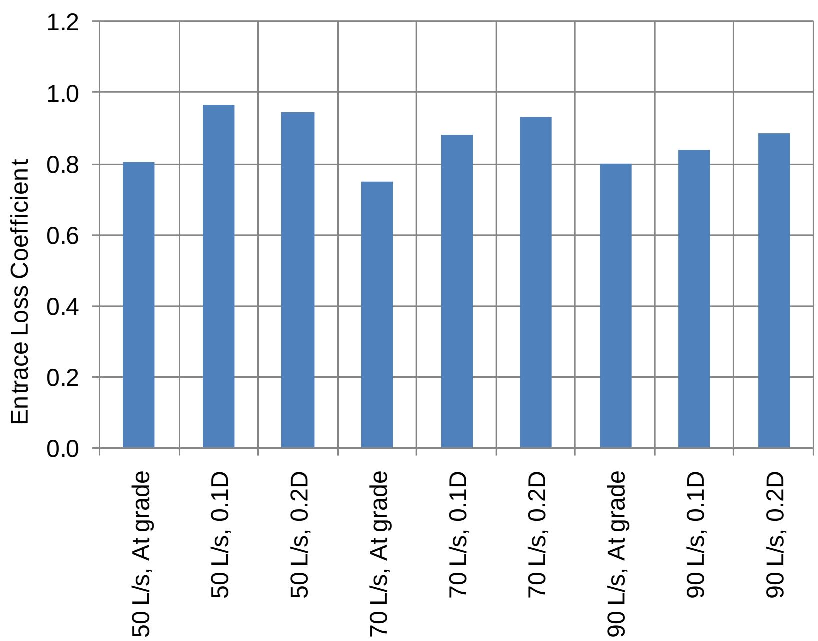

Figure 5.21 Entrance loss coefficients for each combination of discharge and embedment.

5.2 Velocity Distribution Within The Culvert

5.2.1 Velocity Distribution Background

A velocity distribution exists within a culvert barrel due to the friction along the culvert walls. The velocity distribution in a culvert flowing partially full is also influenced by the presence of a free surface. The lower velocity regions near the culvert bed and walls may provide adequate conditions for fish passage; therefore, there is question as to whether the mean velocity is an appropriate criterion for assessing a fish's ability to swim through a culvert. For this research study, this specific velocity criterion was examined by quantifying the velocity distribution and comparing the distribution between culverts placed at grade and embedded. Instead of stating that the velocities are less for embedded culverts, as was the case in Section 5.1.2, the velocity distribution in the culvert is examined more thoroughly.

5.2.2 Cross-Sectional Velocity Distribution

In addition to vertical velocity profiles, cross-sectional velocity distributions were taken at multiple locations along the length of the culvert. Velocity measurements were collected in the *y*-*z* plane (i.e., the culvert cross-section) at five locations along the length of the culvert for each combination of culvert placement and discharge. For each velocity measurement, the ADV sampled at a rate of 25 Hz for 10 minutes. Table 5.3 lists the number of point locations measured per cross-section, the mean number of samples per point location and the percent of good samples per point location. Good samples represent data that have passed the filtering criteria of having a SNR ratio greater than 15 and a CORR greater than 70.

Table 5.3 Summary of processed data for the velocity distribution measurements.

Culvert Placement	Discharge (L/s)	Location Along *x*-axis (m)	Point Locations	Samples / Location	Mean Good* Samples (%)
At grade	50	0.5	31	14633	71.5
At grade	50	1.5	24	15037	38.5
At grade	50	4.0	27	15049	45.9
At grade	50	6.5	28	15052	47.4
At grade	50	7.5	34	15046	58.5

Table 5.3 is continued on the next page.

Table 5.3 (cont'd) Summary of processed data for the velocity distribution measurements.

Culvert Placement	Discharge (L/s)	Location Along *x*-axis (m)	Point Locations	Samples / Location	Mean Good* Samples (%)
0.1*D*	50	0.5	32	15042	60.1
0.1*D*	50	1.5	29	15007	62.9
0.1*D*	50	4.0	30	15003	79.1
0.1*D*	50	6.5	30	15014	78.8
0.1*D*	50	7.5	37	15004	77.7
0.2*D*	50	0.5	43	15020	76.1
0.2*D*	50	1.5	47	15024	82.2
0.2*D*	50	4.0	46	15060	86.4
0.2*D*	50	6.5	51	15010	85.9
0.2*D*	50	7.5	53	14745	84.2
At grade	70	0.5	35	15039	81.1
At grade	70	1.5	35	15060	88.5
At grade	70	4.0	39	15035	86.6
At grade	70	6.5	37	15040	83.4
At grade	70	7.5	41	14571	84.9
0.1*D*	70	0.5	41	15064	88.2
0.1*D*	70	1.5	42	15032	87.6
0.1*D*	70	4.0	43	15029	90.2
0.1*D*	70	6.5	55	15030	92.9
0.1*D*	70	7.5	55	15015	89.3
0.2*D*	70	0.5	52	15011	90.6
0.2*D*	70	1.5	55	15012	86.7
0.2*D*	70	4.0	59	15017	84.6
0.2*D*	70	6.5	60	15021	82.5
0.2*D*	70	7.5	59	15008	79.6
At grade	90	0.5	43	15073	79.2
At grade	90	1.5	47	15043	88.0
At grade	90	4.0	48	15029	89.1
At grade	90	6.5	49	15067	90.2
At grade	90	7.5	47	15038	87.8
0.1*D*	90	0.5	57	15037	77.0
0.1*D*	90	1.5	57	15143	67.1
0.1*D*	90	4.0	57	15038	68.1
0.1*D*	90	6.5	60	15013	83.4
0.1*D*	90	7.5	60	15059	90.4
0.2*D*	90	0.5	61	14782	90.5
0.2*D*	90	1.5	63	15036	92.3
0.2*D*	90	4.0	62	15011	93.6
0.2*D*	90	6.5	66	15009	89.2
0.2*D*	90	7.5	63	15011	88.0

* Good samples represent samples that have passed the filtering criteria.

As shown in Table 5.3, the number of point locations measured per cross-section ranged from 24 to 66. The number of point locations increased with discharge and with embedment due to the increase in flow depth. Of the approximately 15,000 samples, 80% of the samples were considered good (i.e. about 12,000 samples met the filtering criteria).

After filtering the data, a summary of the velocity data collected for each cross-sectional measurement was compiled containing $\overline{u}$, $\overline{v}$, $\overline{w}$, $RMS_{u'}$, $RMS_{v'}$ and $RMS_{w'}$ at each point location within the cross-section, as presented in Appendix I. These data were used to create velocity and turbulence intensity contour plots by means of a software package called Surfer Version 8 by Golden Software (Surfer). Within Surfer, the Radial Basis Function gridding method was used to produce the contour plots. This method is described in the Surfer manual as "quite flexible" and that "it generates the best overall interpretations of most data sets". Grid files were produced for several sets of data and compared using all twelve different gridding methods available in Surfer. The Radial method produced plots that appeared most similar to velocity distributions found in other literature (Chow 1959; Magura 2007).

The ADV was incapable of measuring within 5 cm of the water surface; therefore, there are no data for those locations. For some measurements, the ADV was incapable of measuring more than 5 cm from the water surface due to water bubbles interfering with the ADV signal. For these cases, measurements were taken, but the ADV's sample SNR or CORR did not meet the specified criteria and the measurement was filtered out. Therefore, the results of Surfer's interpolated values near the water surface were verified using an up-looking ADV probe. This probe became available to the research study after the majority of the data had been collected. The up-looking probe was able to fill in the 'gaps' resulting from the limitations of the down-looking ADV probe. The contour results developed using the data from the down-looking ADV only were compared to the contour results developed by combining the down-looking and up-looking measurements. A complete report produced from the comparison is located in Appendix F. It was found that by adding the measurements from the up-looking probe at a discharge of 50 L/s, the discharge found by volume-area integration improved by 1.3%, while the average velocity improved by 1.2%. At 90 L/s, the discharge found by volume-area integration when using the up-looking probe improved by 2.6%, while the average velocity improved by 2.4%. When comparing individual point measurements where the down-looking and up-looking probe measurements overlapped, there was approximately 1 cm/s difference for the points at 50 L/s and approximately 5 cm/s for points at 90 L/s. It was judged that the improvement in the velocity contours produced by the up-looking probe did not warrant the time required to redo all the data collection (i.e. approximately four to six months).

Velocity contour plots were created for the streamwise velocity only. Streamwise velocity is of most concern for fish, with its magnitude being significantly larger than the vertical or transverse velocities. Because of this, fish passage flows through culverts have historically been modeled using one-dimensional flow models. Small samples of the total number of contour plots are shown in the main body of this document. The remaining plots are shown in Appendix G. Before the small samples of plots are presented, the way in which they were checked for quality is explained.

For each cross-sectional flow area plotted, a velocity-area integration was conducted to determine a discharge and mean velocity value, respectively. The values of discharge and mean velocity found by integrating the contour plots was then compared to the discharge measured by the magnetic flow meter and the mean velocity found by dividing the discharge by the measured flow area. This comparison was a method of "checking" the data for problems.

Table 5.4 shows the percent difference between the measured values and calculated values. The percent difference was calculated by subtracting the measured value from the calculated value, then dividing it by the measured value. Figure 5.22 shows the distribution of percent difference in a column chart.

Table 5.4 Comparison of measured and calculated discharge and mean velocity values.

Culvert Placement	Discharge (L/s)	Hole No.	*x*-location (m)	Discharge Difference (%)	Velocity Difference (%)
At grade	50	2	0.5	-7.4	-9.5
At grade	50	5	1.5	n/a	n/a
At grade	50	8	4.0	-12	-8.7
At grade	50	11	6.5	-13	-11
At grade	50	14	7.5	-6.8	-3.8
At grade	70	2	0.5	-3.7	-1.2
At grade	70	5	1.5	-10	-7.7
At grade	70	8	4.0	-6.9	-4.3
At grade	70	11	6.5	-10	-7.9
At grade	70	14	7.5	-4.7	-2.0
At grade	90	2	0.5	-3.4	-0.9
At grade	90	5	1.5	-13	-10
At grade	90	8	4.0	-9.2	-6.9
At grade	90	11	6.5	-9.6	-7.2
At grade	90	14	7.5	-7.6	-5.2
0.1*D*	50	2	0.5	-17	-15
0.1*D*	50	5	1.5	-8.8	-6.9
0.1*D*	50	8	4.0	-6.6	-3.8
0.1*D*	50	11	6.5	-9.0	-6.4
0.1*D*	50	14	7.5	-6.8	-4.3
0.1*D*	70	2	0.5	-9.0	-6.6
0.1*D*	70	5	1.5	-15	-13
0.1*D*	70	8	4.0	-7.4	-5.0
0.1*D*	70	11	6.5	-6.7	-4.3
0.1*D*	70	14	7.5	-8.7	-6.4
0.1*D*	90	2	0.5	-13	-11
0.1*D*	90	5	1.5	-11	-8.9
0.1*D*	90	8	4.0	-8.2	-7.2
0.1*D*	90	11	6.5	-11	-9.0
0.1*D*	90	14	7.5	-9.0	-6.8
0.2*D*	50	2	0.5	-9.6	-7.0
0.2*D*	50	5	1.5	-11	-8.8
0.2*D*	50	8	4.0	-11	-9.1
0.2*D*	50	11	6.5	-8.4	-6.1
0.2*D*	50	14	7.5	-8.2	-5.8
0.2*D*	70	2	0.5	-13	-11
0.2*D*	70	5	1.5	-10	-8.1
0.2*D*	70	8	4.0	-8.4	-6.2
0.2*D*	70	11	6.5	-12	-9.5
0.2*D*	70	14	7.5	-13	-11

Table 5.4 is continued on the next page.

Table 5.4 (cont'd) Comparison of measured and calculated discharge and mean velocity values.

Culvert Placement	Discharge (L/s)	Hole No.	x-location (m)	Discharge Difference (%)	Velocity Difference (%)
0.2*D*	90	2	0.5	-8.8	-6.7
0.2*D*	90	5	1.5	-9.8	-7.7
0.2*D*	90	8	4.0	-10	-8.3
0.2*D*	90	11	6.5	-13	-8.1
0.2*D*	90	14	7.5	-13	-11
		Average Difference =		-9.7	-7.4

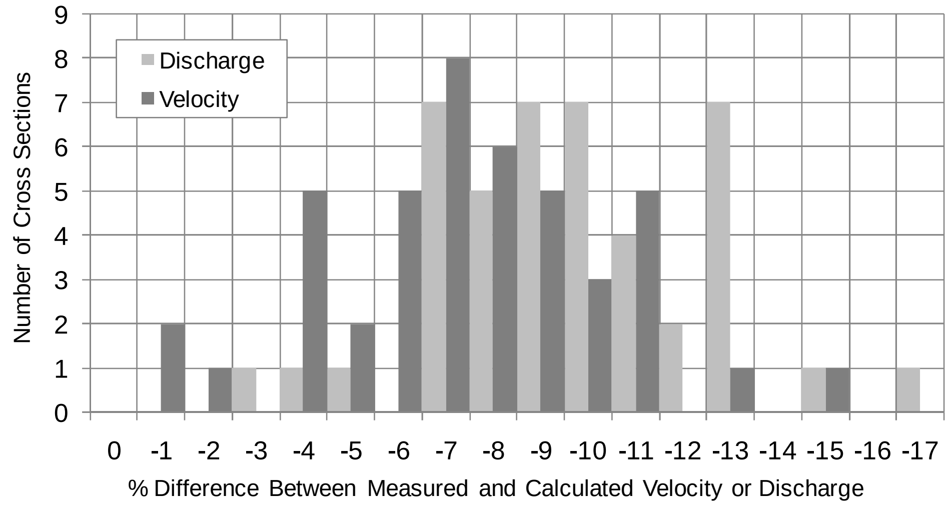

Figure 5.22 Percent difference between measured and calculated velocity and discharge for all measured cross-sections.

As shown in Table 5.4 and Figure 5.22, the largest differences were -17% and -15% for discharge and velocity, respectively. These differences occurred at x = 0.5 m (Hole 2) when the culvert was placed at an embedment of 0.1D for a discharge of 50 L/s. The lowest discharge and velocity errors were -3.4 % and -0.9 %, respectively, occurring at x = 0.5 m (Hole 2) when the culvert was placed at-grade for a discharge of 90 L/s. It is interesting to note that the greatest and least differences occurred at the same location (i.e., x = 0.5 m). The reason for this is uncertain. All calculated values were less than the measured values, with the mean discharge and velocity differences being -9.7 % and -7.4 %, respectively.

These results are somewhat comparable to the results found in other studies. For example, Magura (2007) conducted detailed velocity measurements within a circular pipe that was embedded and back-filled. He found that the difference between the integrated and measured discharges ranged from -10.2 % to 2.8 % with an average of -4.1 %. Knight and Sterling (2000) similarly integrated the point velocities over the cross-section area and found differences ranged from -5.9 % to 4.6%, with a mean of 2.5 %. However, it should be noted that other studies had positive and negative differences, while this study only had negative differences, meaning that the calculated values were always less than the measured values. The reason for this bias is uncertain. It may be somewhat related to the way in which the boundary condition was handled in Surfer. For this research study, a zero velocity boundary was imposed at the culvert wall. In other words, Surfer was forced to produce a very steep gradient from the last velocity measurement near the culvert wall to an imposed velocity of zero at the boundary. However, the overall conclusion from this velocity-area "check" is that the contour plots do not have any significant errors or problems.

Figures 5.23 and 5.24 show contour plots illustrating the velocity distributions measured at certain locations along the length of the culvert. Figure 5.23 has five contour plots with each representing a difference location along the culvert length, while Figure 5.24 has three contour plots with each representing a different culvert placement (i.e., at grade, 0.1D and 0.2D). The common cross-section shown in these two figures is the streamwise velocity distribution measured at $x = 7.5$ m (i.e., near the culvert outlet where the M1 water surface profile has the most significance) with the culvert placed at grade and a discharge of 50 L/s. The small dark diamonds located within each cross-section plot represent the location of the point measurements.

Figure 5.23 shows the velocity distribution for several locations along the length of the culvert for the culvert placed at grade and with a discharge of 50 L/s. It is evident that the velocity distribution is similar once the flow has reached fully developed flow, which was previously examined in Section 5.1.2. This similarity is expected because the water is approximately normal depth throughout the entire length.

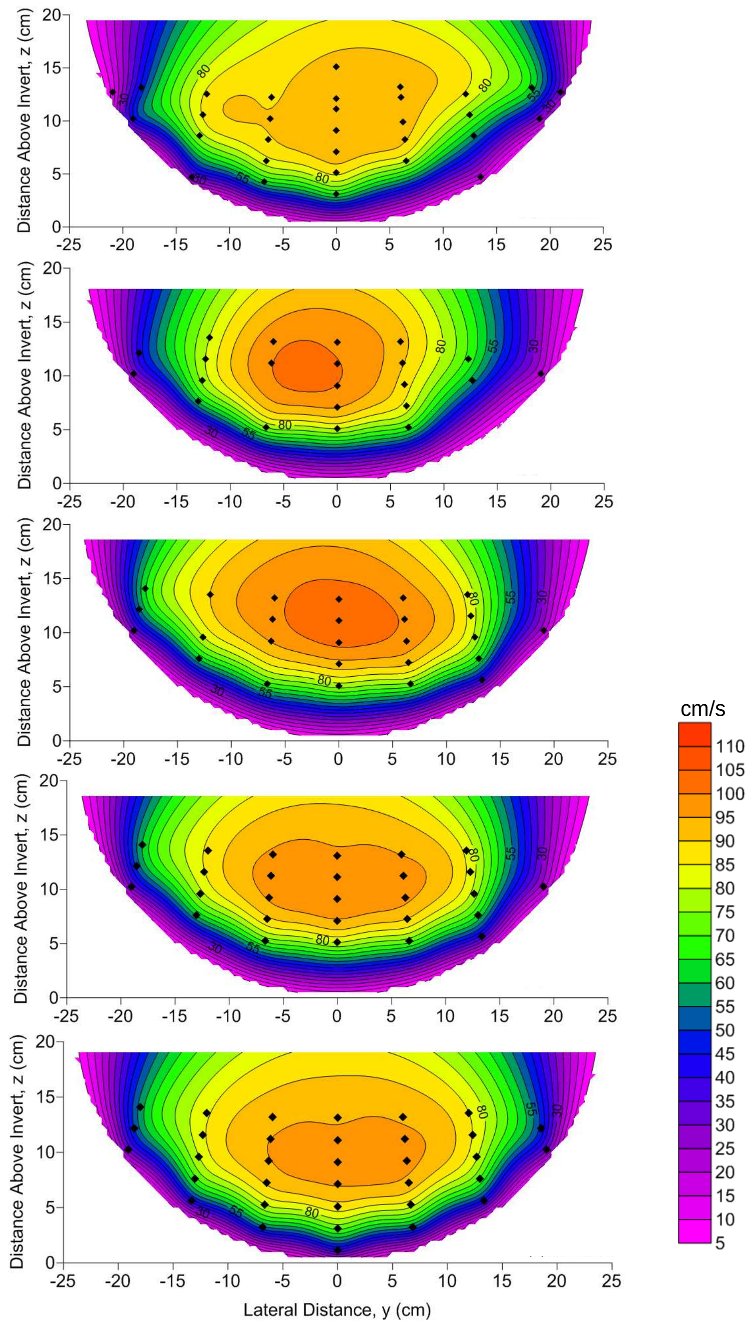

Figure 5.23 Streamwise velocity distributions at x = 0.5, 1.5, 4.0, 6.5 and 7.5 m, shown from top to bottom respectively, for the culvert placed at-grade and a discharge of 50 L/s.

Figure 5.24 shows the changes in velocity distribution among embedment at one location near the culvert outlet. The maximum velocity contours for the culvert placed at grade, at an embedment of 0.1D and at an embedment of 0.2D are approximately

95 cm/s, 70 cm/s and 55 cm/s, respectively. In other words, the maximum velocity decreased by approximately 26% when embedding the culvert 0.1*D* and 42% when imbedding the culvert 0.2*D*.

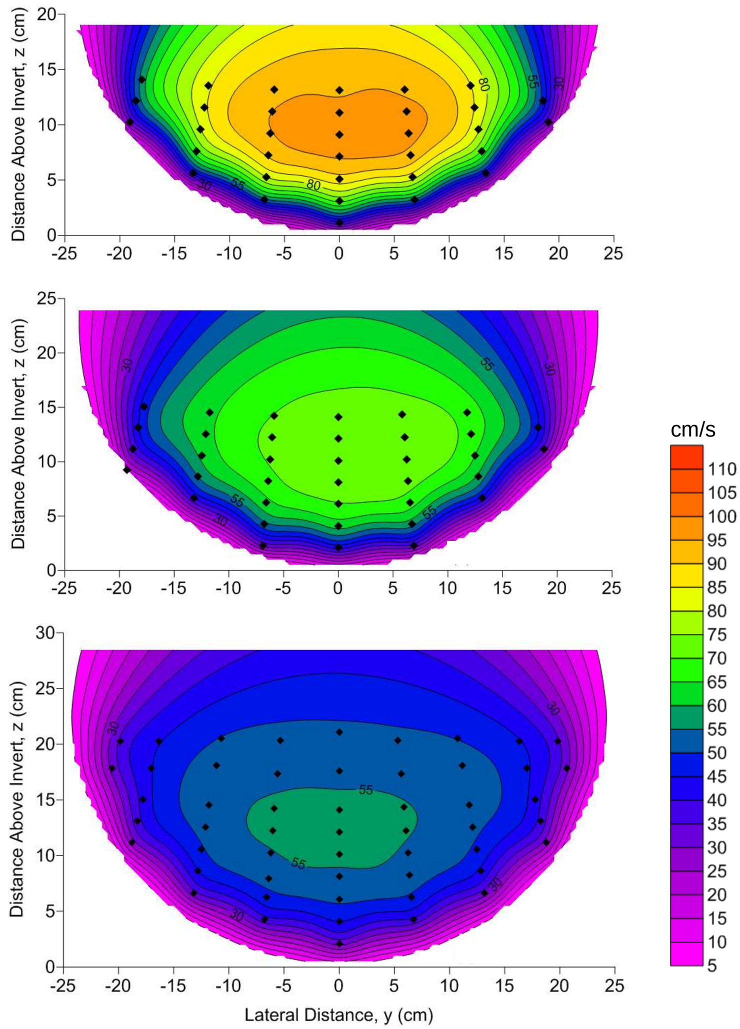

Figure 5.24 Streamwise velocity distributions at x = 7.5 m for the culvert placed at grade, an embedment of 0.1*D* and an embedment of 0.2*D*, shown from top to bottom respectively, for a discharge of 50 L/s.

The results in Figure 5.24 suggest that, for the conditions tested in this research study, a fish has greater area of low velocity when swimming through an embedded culvert, as opposed to a culvert placed at grade. For example, if the fish is able to swim against a velocity of 50 cm/s (i.e., the blue or pink area of the contour plots) then there is more flow area for the fish to swim when the culvert is embedded as opposed to placed at grade. However, it is important to recall that the existence of an M1 water surface profile might not exist throughout the entire length of the culvert if the barrel is long. Therefore, the velocity distribution may not necessarily vary with position along the culvert, as shown in Figure 5.24.

To show that the results are similar among tests in this research study, similar contours plots are shown in Figures 5.25 and 5.26. The common cross-section plot in Figures 5.25 and 5.26 is the streamwise velocity distribution measured at x = 4.0 m (i.e., the middle of the culvert) with the culvert placed at an embedment of 0.1*D* and a discharge of 70 L/s.

Figure 5.25 shows the velocity distribution at different locations along the length of the culvert when the culvert is placed at an embedment of 0.1*D*. All five contour plots have a different velocity distribution, which is expected because of the M1 water surface profile occuring within the culvert. In general, the plots show as slight increase in velocity before a decrease is evident.

Figure 5.26 shows the difference in velocity distributions for different embedments. Placed at grade, the maximum velocity is approximately 105 cm/s. However, with an embedment of 0.1*D* or 0.2*D*, the maximum velocity decreases to approximately 90 cm/s or 70 cm/s, respectively, which corresponds to a decrease of approximately 14% and 33%, respectively.

As mentioned previously, the complete sets of contour plots are located in Appendix G. Color coding of the contour plots is consistent among all plots. Generally, all plots show good symmetry, as was expected with the use of a culvert having annular corrugations. All plots generally show a decrease in maximum velocity with embedment.

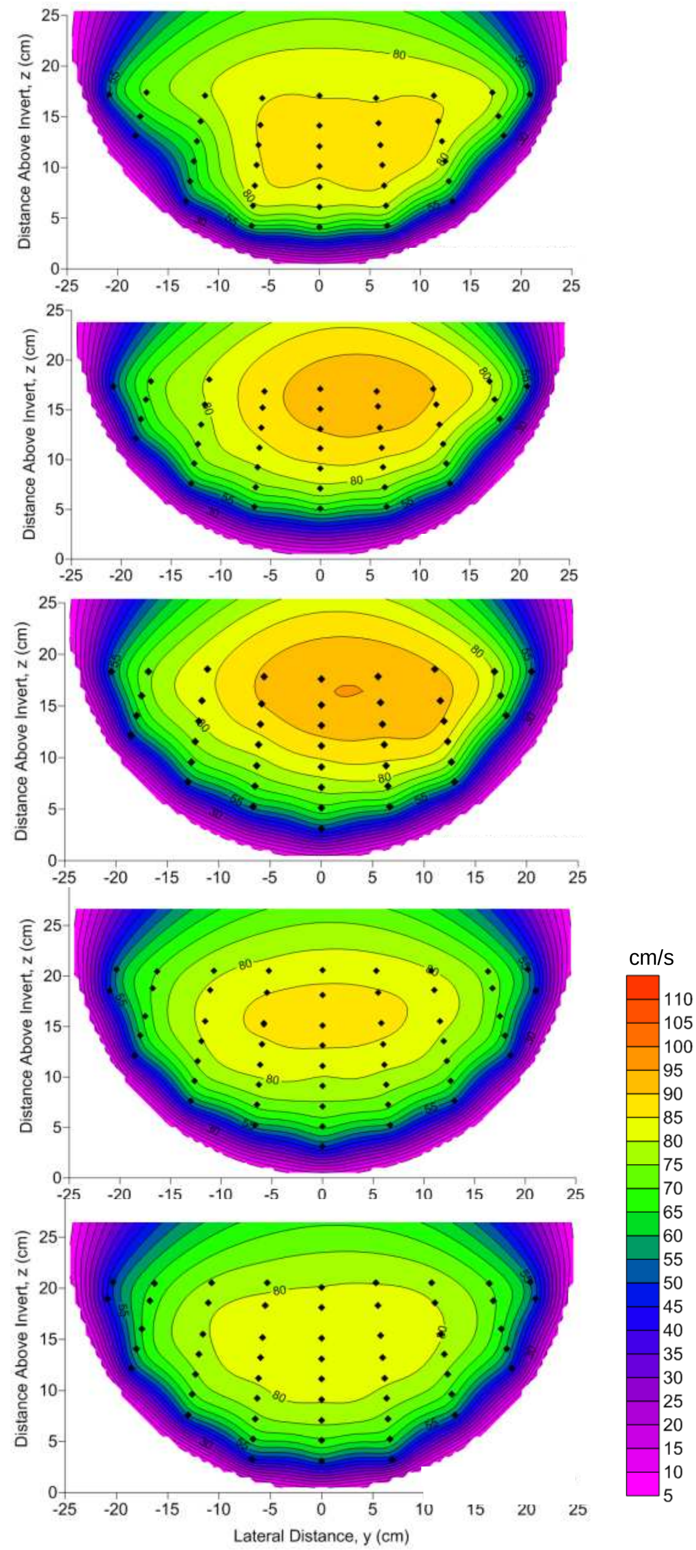

Figure 5.25 Streamwise velocity distributions at x = 0.5, 1.5, 4.0, 6.5 and 7.5 m, shown from top to bottom respectively, for the culvert placed at an embedment of 0.1D and a discharge of 70 L/s.

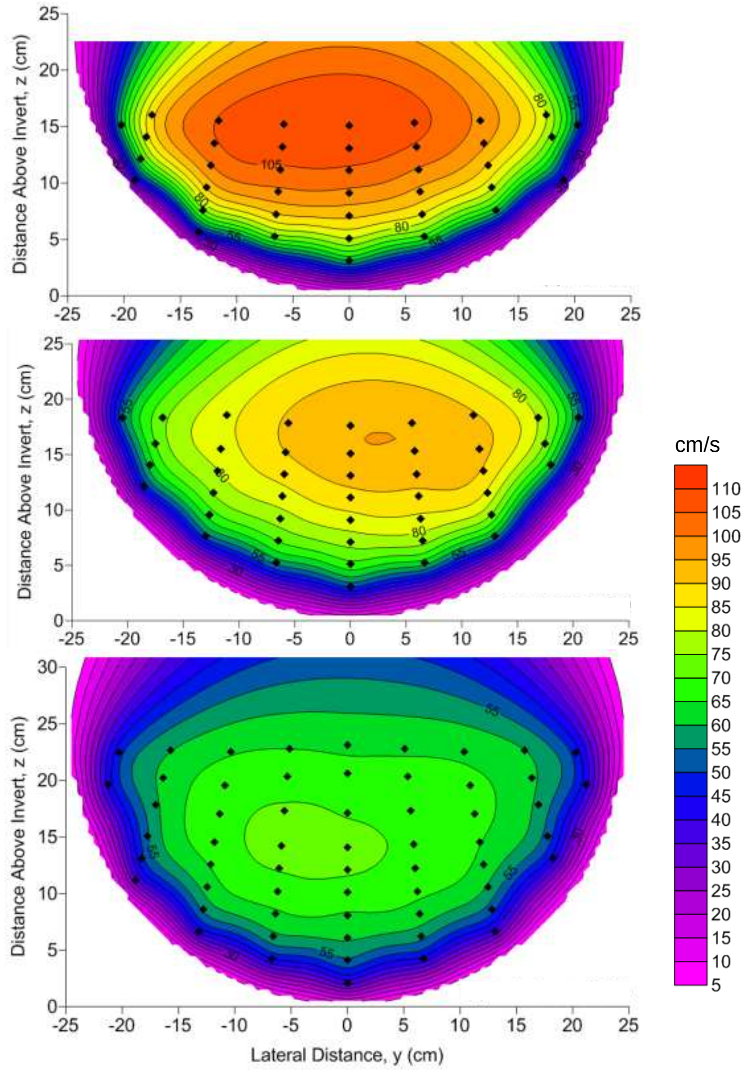

Figure 5.26 Streamwise velocity distributions at x = 4.0 m for the culvert placed at grade, an embedment of 0.1*D* and an embedment of 0.2*D*, shown from top to bottom respectively, for a discharge of 70 L/s.

The mean velocity of each cross-section (i.e., discharge divided by area of the cross-section) is shown in Table 5.5. The mean velocity decreased as the culvert embedment increased. The decrease in mean velocity generally increases with distance downstream due to the M1 water surface profile creating gradually varied flow depths within the culvert barrel. For the work reported herein, on average, embedding the culvert 0.1*D* caused a 15% decrease in the mean velocity, while embedding the culvert 0.2*D* caused a 30% decrease in the mean velocity.

Table 5.5 Mean velocity of each cross-section.

Culvert Placement	Discharge (L/s)	Location Along *x*-axis (m)	Mean Velocity (m/s)	Decrease in Mean Velocity from At-Grade Condition (%)
At grade	50	0.5	0.71	-
At grade	50	1.5	0.78	-
At grade	50	4.0	0.75	-
At grade	50	6.5	0.75	-
At grade	50	7.5	0.73	-
At grade	70	0.5	0.78	-
At grade	70	1.5	0.80	-
At grade	70	4.0	0.81	-
At grade	70	6.5	0.79	-
At grade	70	7.5	0.80	-
At grade	90	0.5	0.83	-
At grade	90	1.5	0.85	-
At grade	90	4.0	0.85	-
At grade	90	6.5	0.87	-
At grade	90	7.5	0.87	-
0.1*D*	50	0.5	0.69	2%
0.1*D*	50	1.5	0.62	21%
0.1*D*	50	4.0	0.60	20%
0.1*D*	50	6.5	0.56	25%
0.1*D*	50	7.5	0.54	26%
0.1*D*	70	0.5	0.70	10%
0.1*D*	70	1.5	0.76	5%
0.1*D*	70	4.0	0.70	14%
0.1*D*	70	6.5	0.66	16%
0.1*D*	70	7.5	0.66	17%
0.1*D*	90	0.5	0.75	10%
0.1*D*	90	1.5	0.78	9%
0.1*D*	90	4.0	0.78	8%
0.1*D*	90	6.5	0.74	14%
0.1*D*	90	7.5	0.73	16%
0.2*D*	50	0.5	0.53	25%
0.2*D*	50	1.5	0.50	36%
0.2*D*	50	4.0	0.45	40%
0.2*D*	50	6.5	0.43	43%
0.2*D*	50	7.5	0.43	40%
0.2*D*	70	0.5	0.66	15%
0.2*D*	70	1.5	0.61	24%
0.2*D*	70	4.0	0.55	32%
0.2*D*	70	6.5	0.53	32%
0.2*D*	70	7.5	0.54	33%

Table 5.5 is continued on the next page.

Table 5.5 (cont'd) Mean velocity of each cross-section.

Culvert Placement	Discharge (L/s)	Location Along *x*-axis (m)	Mean Velocity (m/s)	Decrease in Mean Velocity from At-Grade Condition (%)
0.2*D*	90	0.5	0.67	20%
0.2*D*	90	1.5	0.65	24%
0.2*D*	90	4.0	0.62	27%
0.2*D*	90	6.5	0.60	31%
0.2*D*	90	7.5	0.61	29%

5.2.3 Turbulence Intensity Distributions

Turbulence is a physical characteristic of the flow in a stream that is becoming the focus of more recent fish passage studies. Since the velocity was measured at such a high frequency in this research study, the streamwise turbulence intensity (*TI*) distribution was also calculated and presented. An in depth analysis regarding *TI* is not part of this research study, instead the data will be presented and brief comments will be provided.

TI is generally defined as the root-mean-square of the velocity fluctuations at a particular location divided by the mean velocity at the same location over the same time period, as shown in Equations 4.9 to 4.11. The key part of that definition is the use of the mean velocity measured at a particular point location as the reference value. However, in this work, it was decided that the mean velocity of the flow field during normal flow conditions would be more appropriate in the context of culvert designs for fish passage. For example, when designing culverts for fish passage, the mean velocity of the flow is easily calculated using discharge, flow depth and culvert geometry, while the mean velocity at each point measurement is virtually impossible to know unless it is measured. There is also the issue of comparability of results. If the normalizing or reference velocity is different for each *TI* value, then the *TI* are not likely very comparable. In order to compare the *TI* results found using both reference velocities, *TI* distribution plots were created using both the mean velocity and the specific point velocity for an arbitrarily chosen culvert configuration of the culvert placed at grade with a discharge of 50 L/s, as shown in Figure 5.27. A comparison was not made for all combination of embedment or discharge. In Figure 5.27, the contour plots on the left use the average streamwise velocity measured at a particular point, while the contour plots on the right use the mean velocity of the flow field to calculate the *TI* in the *x*-direction.

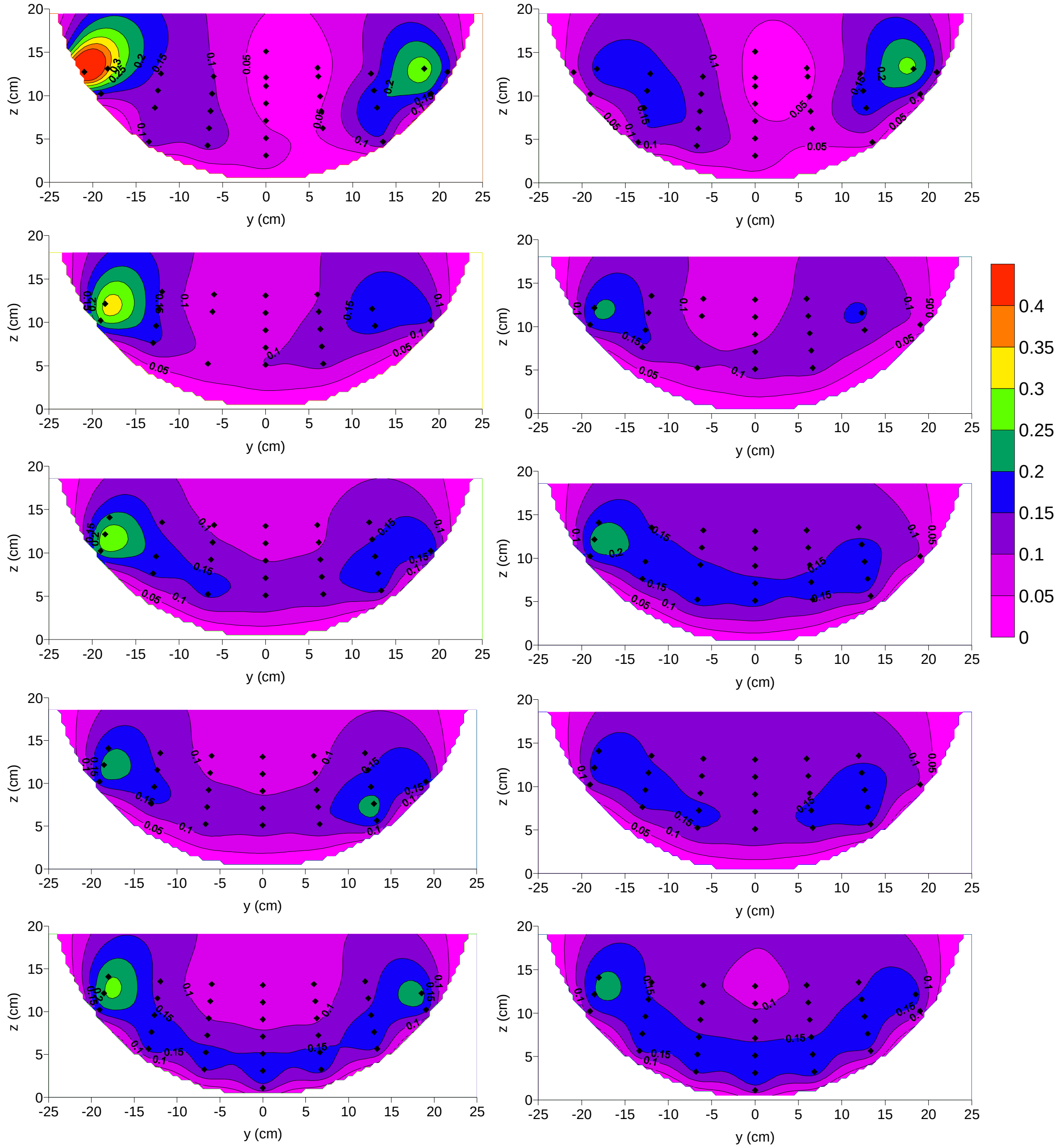

Figure 5.27 *TI* distributions at x = 0.5, 1.5, 4.0, 6.5 and 7.5 m, shown from top to bottom respectively, for the culvert placed at-grade and a discharge of 50 L/s, where the left side represents the method using each specific point velocity, while the right side represents the method using the cross-sectional mean velocity.

When visually comparing the left and right sides of Figure 5.27, the difference between the two methods is minimal. The remainder of the contour plots were created using the mean velocity of the flow field during normal flow conditions as the reference velocity. The plots on the right side of Figure 5.27 shows that the maximum *TI* is approximately 0.2 and occurs at a location near to the edge of the cross-section close to the water surface. Figures 5.28 and 5.29 accompany Figure 5.27 to show a series of contour plots that compare one common cross-section plot to the other locations along the length of the culvert, the other discharges, and the other culvert placements. The common cross-section shown in all three figures is the streamwise *TI* measured at x = 7.5 m (i.e., near the culvert outlet) with the culvert placed at grade and a discharge of 50 L/s.

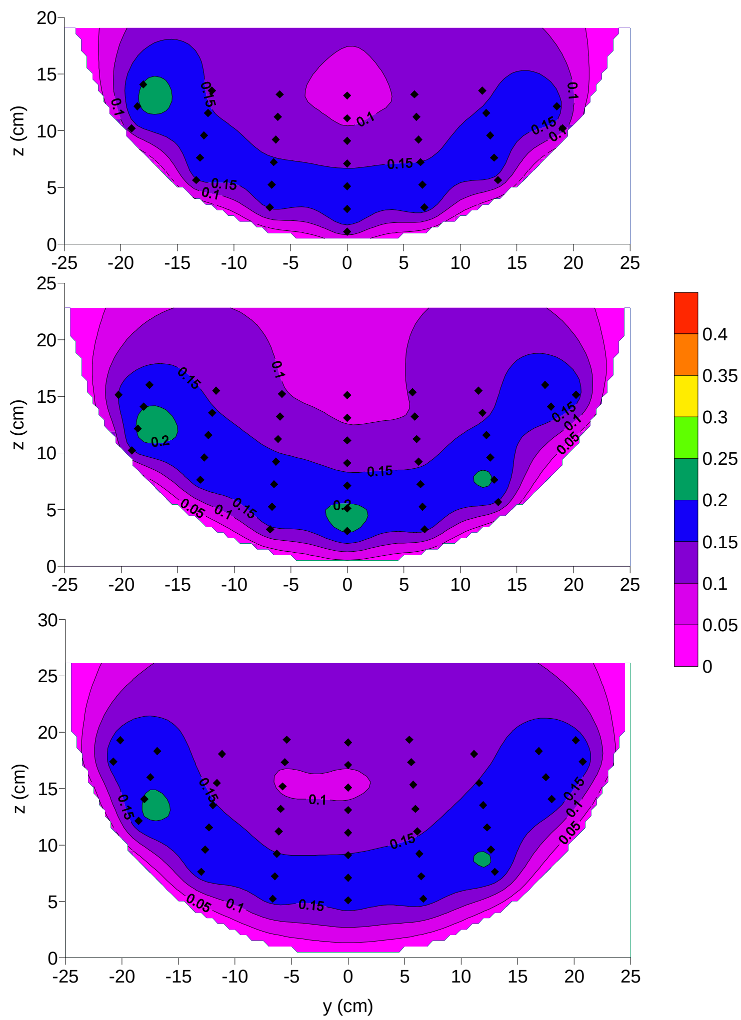

Figure 5.28 *TI* distributions at x = 7.5 m for the culvert placed at-grade and discharges of 50 L/s, 70 L/s and 90 L/s, shown from top to bottom respectively.

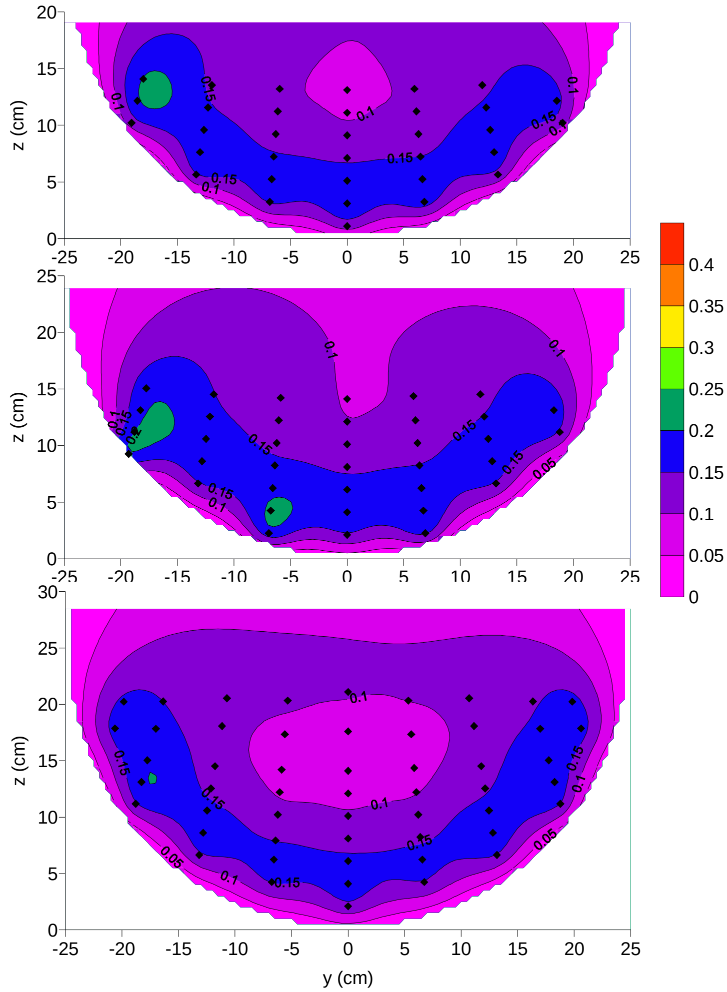

Figure 5.29 *TI* distributions at x = 7.5 m for the culvert placed at grade, an embedment of 0.1D and an embedment of 0.2D, shown from top to bottom respectively, for a discharge of 50 L/s.

In general, the *TI* is 0.3 or less, with the majority of the cross-section containing *TI* of approximately 0.1. Increasing the discharge does not change the distribution significantly, as shown in Figure 5.28. Increasing the embedment depth, also does not appear to greatly affect the *TI* distribution. Figure 5.29 shows that the TI of 0.3 disappears with an embedment of 0.2D; however, this is not a consistent trend when considering all of the contour plots showing the different combinations of discharge and location along culvert. The complete sets of *TI* contour plots are located in Appendix G. Color coding of the contour plots is consistent among all plots.

5.2.4 Flow Area Less than the Mean Velocity of the Flow

DFO recommend that the mean velocity of the flow within a culvert should not exceed the capability of the weakest swimming fish (Katopodis 1992). However, there is question as the whether the mean velocity is an appropriate criterion for assessing a fish's ability to swim through a culvert, especially since fish have the natural ability to find the low velocity zones (Behlke et al. 1991; Lang et al. 2004). For this reason, the amount of flow area below the mean velocity of that in the cross-section is of interest.

Figure 5.30 shows contour plots near the culvert outlet (which is where the fish would enter the culvert) at x = 7.5 m (Hole 14). These plots are of the streamwise velocity non-dimensionalized by the mean velocity of the flow for the culvert placed at-grade, or in other words, the culvert operating under normal flow conditions. The dark shaded area represents the area within the cross-section that has a velocity greater than the mean velocity, while the light shaded area represents a velocity less than the mean velocity.

Figure 5.30(a) shows that the maximum velocity within the cross-section for the culvert placed at-grade is approximately 1.3 times the mean velocity. When the culvert was embedded 0.1*D* and 0.2*D*, the maximum velocity reduced to approximately 1.0 and 0.7 times the mean velocity, as shown in Figures 5.30(b) and 5.30(c), respectively. Also, it is evident from Figure 5.30 that the amount of light shaded area increases with embedment, which means that there is more area within the cross-section for the fish to potentially swim. Similar plots are shown in Appendix G for the remaining cross-sections. The plots in Appendix G show that when the culvert was placed at an embedment of 0.2*D*, the velocities measured within the cross-section are less than the mean velocity of the flow field for normal flow conditions, except near the culvert entrance (i.e., at x = 0.5 m).

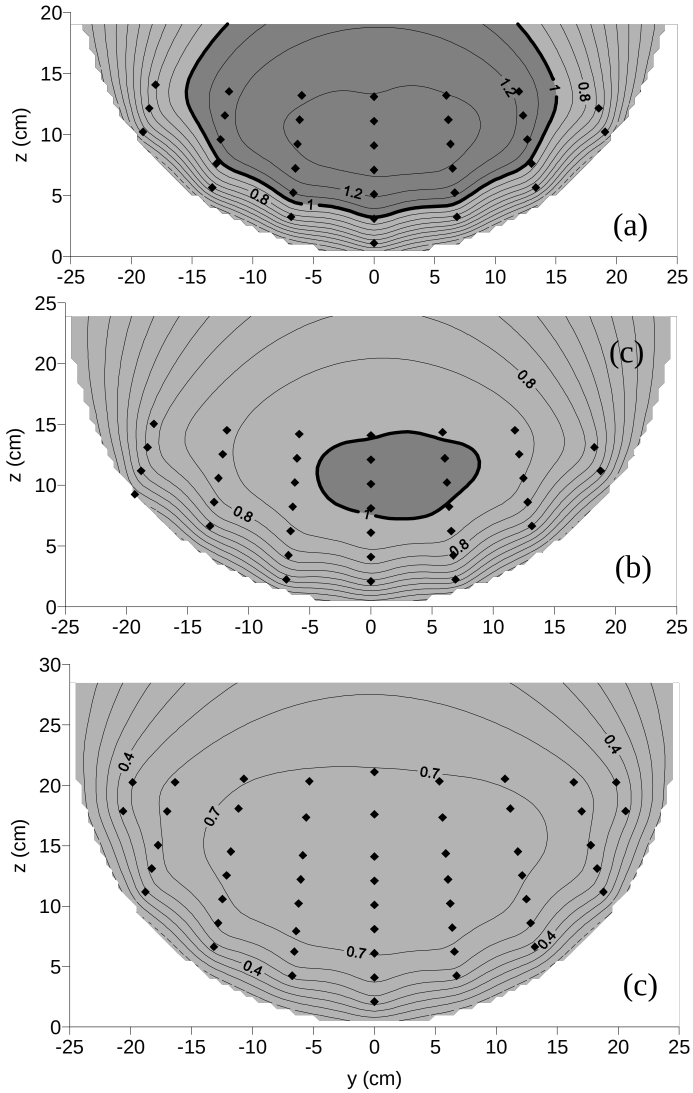

Figure 5.30 Distribution of streamwise velocity non-dimensionalized by the mean velcocity of the flow field for the at-grade condition at x = 7.5 m for a discharge of 50 L/s and culvert placed (a) at-grade, (b) at an embedment of 0.1*D*, and (c) at an embedment of 0.2*D*.

Table 5.6 lists the percent of flow area less than the mean velocity calculated during normal flow conditions for each cross-section measured along the culvert length. When the culvert was placed at grade, on average approximately 44% of the flow area was less than the mean velocity of the flow field. When the culvert was placed at an embedment of 0.1*D* and 0.2*D*, on average approximately 70% and 98% of the flow field was less than the mean velocity of the flow field for normal flow conditions. These results show that for normal flow conditions (i.e., the culvert placed at grade), just less than half of the flow area has a velocity less than the mean. Therefore, in many instances, use of a mean velocity criterion could be excessive in terms of a specification for fish passage. With embedment causing an M1 water surface profile throughout the entire length of the culvert, the hydraulic conditions for fish passage are improved, at least from a velocity perspective.

Table 5.6 Flow area less than the mean velocity for at-grade conditions.

Culvert Placement	Discharge (L/s)	Hole No.	*x*-location (m)	Flow Area Less than the Mean Velocity during At-Grade Conditions (%)
At grade	50	2	0.5	43%
At grade	50	5	1.5	58%
At grade	50	8	4.0	47%
At grade	50	11	6.5	48%
At grade	50	14	7.5	41%
At grade	70	2	0.5	38%
At grade	70	5	1.5	44%
At grade	70	8	4.0	42%
At grade	70	11	6.5	45%
At grade	70	14	7.5	39%
At grade	90	2	0.5	38%
At grade	90	5	1.5	52%
At grade	90	8	4.0	42%
At grade	90	11	6.5	43%
At grade	90	14	7.5	41%
0.1*D*	50	2	0.5	53%
0.1*D*	50	5	1.5	76%
0.1*D*	50	8	4.0	74%
0.1*D*	50	11	6.5	94%
0.1*D*	50	14	7.5	92%
0.1*D*	70	2	0.5	59%
0.1*D*	70	5	1.5	60%
0.1*D*	70	8	4.0	61%
0.1*D*	70	11	6.5	70%
0.1*D*	70	14	7.5	81%
0.1*D*	90	2	0.5	67%
0.1*D*	90	5	1.5	61%
0.1*D*	90	8	4.0	56%
0.1*D*	90	11	6.5	78%
0.1*D*	90	14	7.5	77%

Table 5.6 is continued on the next page.

Table 5.6 (cont'd) Flow area less than the mean velocity for at-grade conditions.

Culvert Placement	Discharge (L/s)	Hole No.	*x*-location (m)	Flow Area Less than the Mean Velocity during At-Grade Conditions (%)
0.2*D*	50	2	0.5	91%
0.2*D*	50	5	1.5	100%
0.2*D*	50	8	4.0	100%
0.2*D*	50	11	6.5	100%
0.2*D*	50	14	7.5	100%
0.2*D*	70	2	0.5	100%
0.2*D*	70	5	1.5	100%
0.2*D*	70	8	4.0	100%
0.2*D*	70	11	6.5	100%
0.2*D*	70	14	7.5	100%
0.2*D*	90	2	0.5	83%
0.2*D*	90	5	1.5	100%
0.2*D*	90	8	4.0	100%
0.2*D*	90	11	6.5	100%
0.2*D*	90	14	7.5	100%

5.2.5 Velocity Distribution Prediction Using Ead et al. (2000)

Being able to predict the velocity distribution within the culvert can be helpful for culvert designs. For example, if a target fish species and size are known, then one can calculate the velocity distribution within the culvert to ensure that there is physically enough space within the culvert where velocities are low enough to accommodate the fish's swimming ability.

Ead et al. (2000) expanded the Prandtl-von Karman equation for one-dimensional vertical velocity distribution for the rough flow regime (Equation 2.2) to account for non-central velocity predictions. Their research studied the velocity distribution in turbulent open-channel flow in a circular corrugated pipe placed at grade. Therefore, velocity measurements taken when the culvert was placed at grade during this research study were compared to the results found using the Ead et al. (2000) equations (i.e., Equations 2.3 to 2.8).

Characteristics measured during this research study, such as discharge, culvert slope, culvert diameter, specific point measurement locations (i.e., the z and y coordinate identifying its location within the culvert cross-section), were inserted into Equations 2.3 to 2.8. The shear velocities at the central axis required in Equation 2.8 were calculated earlier and are shown in Table 5.2. The Ead et al. (2000) equations provided a streamwise velocity at the specified coordinates. The measured streamwise velocity was compared to the calculated streamwise velocity. Table 5.7 shows the measured and calculated streamwise velocity at x = 1.5 m for when the culvert was placed at grade with a discharge of 70 L/s.

Table 5.7 Streamwise velocity comparison between measured and calculated using Ead et al. (2000) equations at x = 1.5 m and the culvert placed at grade with a discharge of 70 L/s.

Lateral Distance (m)	Distance Above Invert (m)	Streamwise velocity measured (m/s)	Streamwise velocity calculated (m/s)	Percent Error
0.00	0.15	1.05	1.06	-1%
0.00	0.13	1.06	1.04	2%
0.00	0.11	1.06	1.02	4%
0.00	0.09	1.05	0.98	6%
0.00	0.07	1.01	0.94	7%
0.00	0.05	0.94	0.88	7%
0.06	0.15	0.98	1.01	-3%
0.06	0.13	0.97	1.01	-4%
0.06	0.11	0.95	1.01	-7%
0.06	0.09	0.91	0.99	-8%
0.06	0.07	0.87	0.94	-8%
0.07	0.05	0.81	0.88	-9%
0.12	0.16	0.88	0.92	-4%
0.12	0.14	0.83	0.93	-10%
0.12	0.12	0.76	0.94	-19%
0.13	0.10	0.69	0.96	-28%
0.17	0.16	0.84	0.69	22%
0.18	0.14	0.78	0.70	11%
0.19	0.12	0.67	0.72	-7%
0.20	0.17	0.75	0.49	54%
0.20	0.16	0.69	0.49	41%

Table 5.7 shows that the average percent error was 2%. The maximum and minimum percent errors were 54% and -28%, respectively. The percent error generally increases

with lateral distance from the culvert centerline. Results for all 15 cross-section comparisons can be seen in Appendix H. The results in Appendix H also show that the percent difference between measured and calculated streamwise velocity increase with lateral distances from the culvert centerline.

The average, minimum, maximum and standard deviation of percent error found for each cross-section between the measured and Ead et al. (2000) predictions are summarized in Table 5.8. A negative percent error means that the measured velocity was less than the predicted value, while a positive percent error means the measured velocity was greater than the predicted value. The overall average error was 0.7%. The average error was greatest for cross-sections with discharges of 50 L/s.

Table 5.8 Percent error between measured streamwise velocity and calculated streamwise velocity using Ead et al. (2000) equations.

Discharge (L/s)	Hole No.	Average	Maximum	Minimum	Std. Dev.
50	2	15	450	-66	108
50	5	-11	3	-34	12
50	8	-9	3	-40	12
50	11	-10	1	-40	12
50	14	-6	10	-30	9
70	2	4	39	-34	17
70	5	2	54	-28	19
70	8	-1	33	-23	12
70	11	-4	20	-38	12
70	14	-2	18	-24	8
90	2	15	42	1	9
90	5	4	44	-11	13
90	8	2	46	-17	15
90	11	3	35	-36	13
90	14	8	41	-13	10
Average percent error =		0.7			

Because there appears to be a greater difference between the measured and calculated streamwise velocity with increased lateral distance from culvert centerline, further analysis was conducted. The lateral distance from the culvert centerline was categorized into four groups: a lateral distance of 0 m (i.e., centerline), a lateral distance between 0 m and 0.10 m, a lateral distance between 0.11 m and 0.15 m, and a lateral distance between 0.16 m and 0.25 m (which is the culvert edge). For each of the 15 cross-sections, the average, maximum and minimum percent error occurring in each category was determined. These statistical results for each cross-section are shown in Appendix H.

Figure 5.31 shows the average difference between the measured streamwise velocity and the calculated streamwise velocity for each category. The average differences between measured and calculated velocities at the centerline and to a lateral distance of 0.10 m are 5% or less for all discharges measured. Between a lateral distance of 0.11 m and 0.15 m, the mean difference is between 2% and -22%. Between a lateral distance of 0.16 m and the side of the culvert, the mean difference ranges from 11% go 23%. The greatest difference occurs near the edge of the culvert away from the centerline. Measured velocities are generally less than calculated velocities at lateral distances of 0.11 m to 0.15 m (which equates to 44% to 60% of the radius), while measured velocities are greater than calculated at lateral distances greater than 0.16 m (which equates to 65% to 100% of the radius).

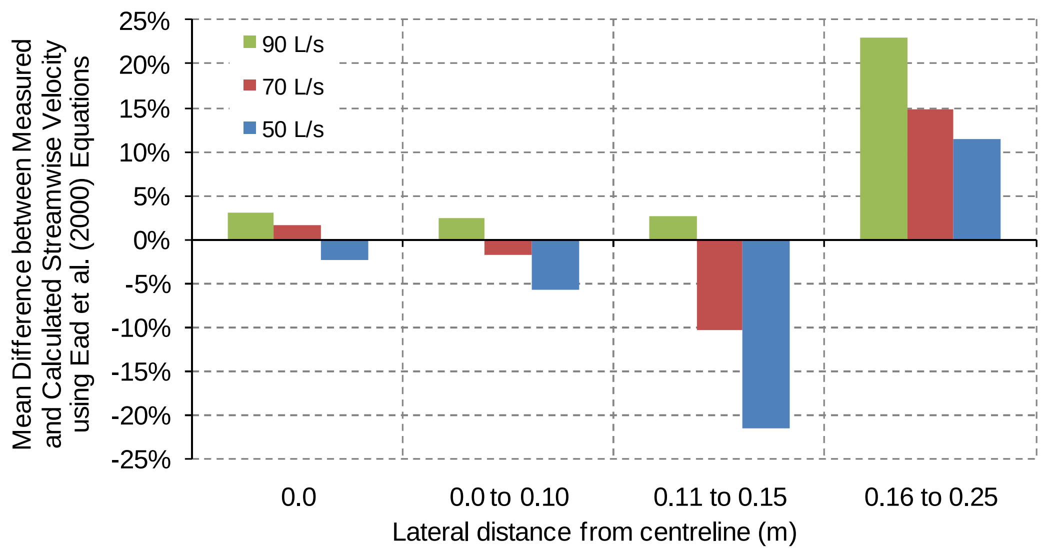

Figure 5.31 Streamwise velocity differences between measured and calculated using Ead et al. (2000) equations with lateral distance from culvert centerline.

To conclude, the Ead et al. (2000) equations adequately predict streamwise velocities near the centerline of the culvert. However, they do not appear to predict streamwise velocities near the boundary of the culvert with very good accuracy, and the boundary areas are of the most concern for fish passage.

5.2.6 Flow Area Analysis

Observations of fish movement indicate that the zone in which they occupy within a culvert can be relatively localized and does not include the full cross-section (House et al. 2005). These observations have led to methods of predicting the percentage of flow within a cross-section containing velocities less than a given velocity (White 1996, House et al. 2005, Magura 2007). The idea is that the extent of the occupied zone can be estimated during the design process. A similar analysis was conducted for this research study.

For each contour plot, the amount of flow area above and below each contour (spaced at 5 cm/s intervals) was found using Surfer Version 8. In other words, there is one datum point for each 5 cm/s contour for each of the cross-sections and discharges. This information was then used to create graphs of the percent of flow area less than a certain velocity. The velocity was non-dimensionalized using either the mean velocity of the flow for normal flow conditions (i.e., the culvert placed at grade) or the mean velocity of each particular cross-section.

Figure 5.32 presents the measured velocity non-dimensionalized by the mean velocity of the flow for the culvert placed at grade, or in other words, with the culvert operating under normal flow conditions (i.e., all of the data have been normalized using the three mean velocities values, one for each discharge condition). Figure 5.32 shows that for a given non-dimensionalized velocity, the percentage of flow area less than a certain velocity value increases with culvert embedment. For example, with the culvert placed at grade, approximately 40% of the flow area is less than the mean velocity. However, with the culvert placed at an embedment of 0.1*D*, approximately 70% of the flow area is less than the mean velocity, or with the culvert placed at and embedment of 0.2*D*, upwards of 100% of the flow area is less than the mean velocity of the culvert under normal conditions. However, with this approach to non-dimensionalizing the data, it is to be expected that the embedment results would shift to the left, and thus it is possible to have 100% of the flow area less than the mean velocity during normal flow conditions.

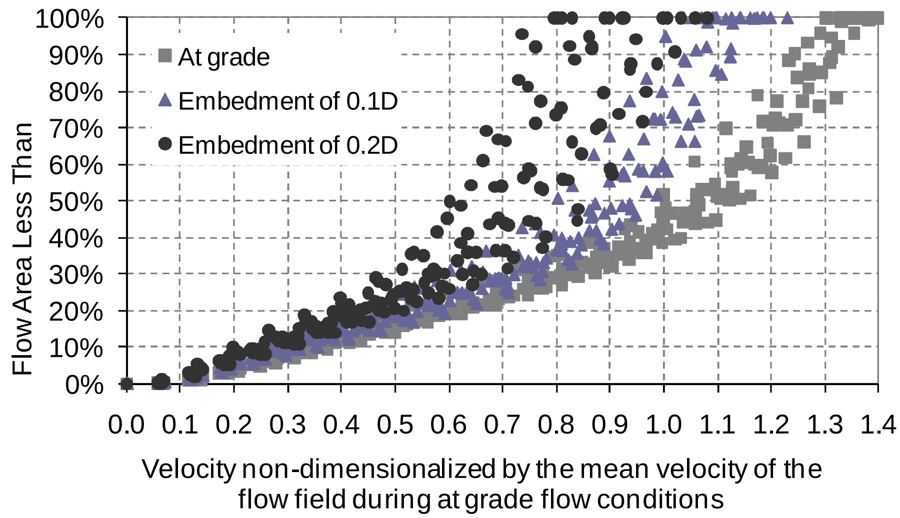

Figure 5.32 Cumulative percentage of the total cross-sectional area where the velocity is non-dimensionalized using the mean velocity that would occur for normal flow conditions (i.e., the culvert placed at grade).

The measured velocity was also non-dimensionalized using the mean velocity of the flow field for each particular cross-section. Using these values, the cross-sectional flow area was similarly expressed as a cumulative percentage of the total cross-sectional area, as shown in Figure 5.33. This method of non-dimensionalizing the velocity causes the data to approximately collapse onto one curve, independent of embedment.

The results shown in Figure 5.33 are comparable to previous studies (House et al. 2005, Magura 2007) where their resulting curve was similarly mildly nonlinear. Their results also collapsed onto one curve for all cross-sections regardless of culvert placement, discharge or location along the length of the culvert. Figure 5.34 shows the curve found in the Magura (2007) study along with the data presented in 5.33. The results found in Magura (2007) do not fully collapse onto the curve found in this study because it is shifted slightly lower by approximately 5% from approximately 0.0 to 0.8 on the *x*-axis. Beyond 0.8 on the *x*-axis, the Magura (2007) curve falls within the spread of data collected in this research study. Magura (2007) used a 0.6 m diameter culvert at various culvert slopes, backfilled with aggregate material.

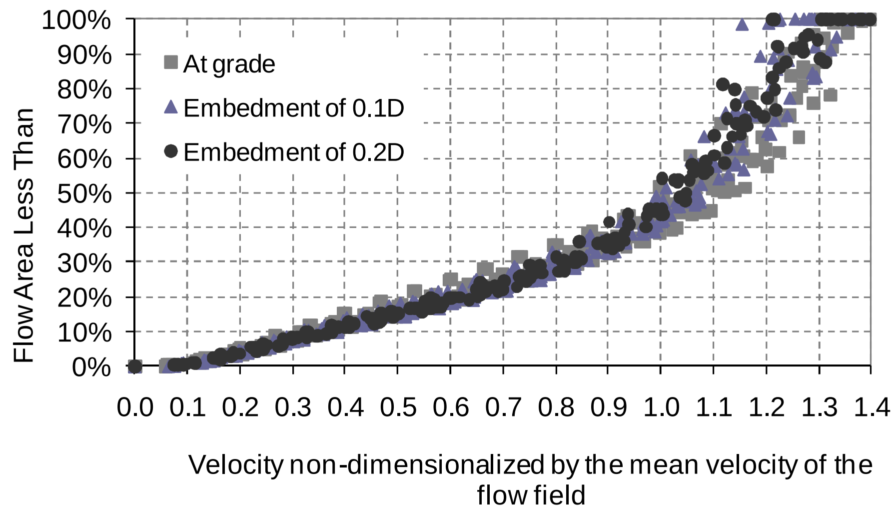

Figure 5.33 Cumulative percentage of the total cross-sectional area where the velocity is non-dimensionalized using the mean velocity of each particular cross-section.

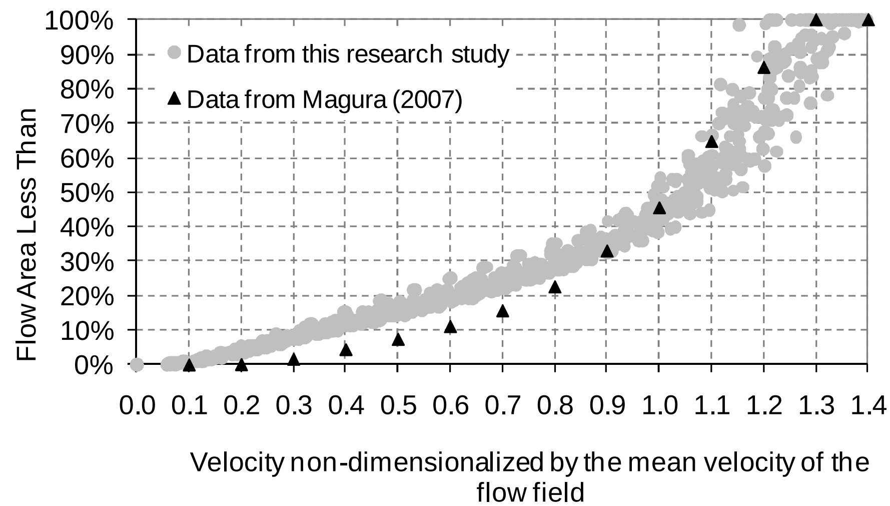

Figure 5.34 Cumulative percentage of the total cross-sectional area with respect to non-dimensionalized velocity using mean velocity of the flow field compared to results found in Magura (2007).

The reason for the difference in results between this research study and Magura (2007) are uncertain; however, one reason may be attributed to the backfill material. Also, Magura (2007) studied several difference culvert slopes, while this research study only had one slope. Another difference between Magura (2007) and this study was the way in which the boundary condition was handled. This research study forced a zero flow boundary at the culvert edges, while Magura (2007) did not force a zero flow boundary.

Although the spatial distribution of the flow areas of a particular velocity were not assessed, it has been shown in previous literature (Chow 1959; Magura 2007; Richmond et al. 2007) and within this research study that the areas of similar velocity are "clumped" together rather than distributed throughout the cross-section. In other words, a flow area with a certain velocity will likely be located in a contiguous semi-circular ring around the culvert boundary. It will not be spread out in various locations throughout the cross-section. This is significant because the flow area on the *y*-axis of Figures 5.33 and 5.34 can be assumed to be contiguous instead of scattered about the cross-section, which means that that flow area can be directly related to the size of a target fish species using the culvert.

CHAPTER 6
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

Circular corrugated steel pipes are commonly used as stream crossing structures because of their lower comparable cost to other alternatives. Culverts, however, can restrict the width of the channel, thereby increasing the velocity of the flow through the culvert. High velocities can act as a barrier to fish migrating upstream. In Canada, the legislated requirement for fish passage is outlined in Section 20 of the Fisheries Act (R.S., 1985, c. F-15). It is generally interpreted such that a fish passage delay should not exceed three days more than once every 10 years and that the mean cross-sectional velocity in a culvert should not be greater than the capability of the weakest swimming fish (Katopodis 1992; Saskatchewan Environment 1995; Alberta Transporation 2001). One method of reducing the culvert flow velocities for part-full flow conditions is to embed the culvert invert below the bed grade level. The work reported in this thesis document is focussed on better understanding the hydraulics of embedded culverts.

A physical model of a culvert installation was set up in the Hydrotechnical Laboratory of the Department of Civil and Geological Engineering at the University of Saskatchewan. An annular CSP culvert was used, with a diameter of 500 mm, length of 8.0 m, and slope of approximately 0.75%. Nine combinations of culvert placement and discharge were tested, including the culvert placed at-grade, at an embedment of 0.1*D* and at an embedment of 0.2*D* for discharges of 50 L/s, 70 L/s and 90 L/s. Detailed velocity measurements were made at five cross-section locations along the length of the culvert, while centerline vertical velocity profiles were collected at an additional five locations. Flow depths were recorded at 15 locations along the length of the culvert and at locations upstream and downstream of the culvert.

For all tests conducted in this research study, the normal depths were greater than the critical depths; therefore, the flow was subcritical and the channel was classified as having a mild slope. For tests in which the culvert was placed at grade, uniform flow conditions were established throughout the length of the culvert. However, uniform flow conditions did not occur for culvert placement depths of $0.1D$ and $0.2D$ due to backwater conditions throughout the length of the culvert (i.e., the tailwater depths were greater than the normal depth). These backwater conditions created a M1 water surface profile within the culvert. The extent of the M1 profile throughout the length of the culvert was found by collecting flow depths along the length of the culvert and by using an analytical approach. All measured water surface profiles showed a typical drop at the entrance, followed by a rise, which is consistent with profiles found in previous literature. An M1 water surface profile extended throughout the length of the entire culvert for the two embedment conditions reported herein. The measured water surface profiles were consistent with the analytical results.

The significance of an M1 water surface profile throughout the length of the culvert is that, for a given discharge, the flow depths are greater than flow depths for normal flow conditions. This, in turn, results in lower mean velocities, which relates directly to the fish passage criterion that states that the mean cross-sectional velocity in a culvert should not be greater than the capability of the weakest swimming fish.

For this research study, vertical velocity profiles were taken at multiple locations along the length of the culvert. After analyzing the boundary layer growth and centerline vertical velocity profiles, the flow was assumed to be fully developed after $x = 3.0$ m. When comparing centerline vertical velocity profiles among culvert placements, it was found that the greater the embedment, the lower the velocity. The maximum velocity for at-grade conditions was approximately 1.3 times the mean velocity of the flow field. However, the maximum vertical velocity for the culvert embedment of $0.1D$ and $0.2D$ was approximately 1.1 and 0.8 times the mean velocity of the flow field for at-grade conditions, respectively.

For this research study, embedding the culverts reduced the velocities throughout the length of the culvert, which in turn, reduced the total head loss. Although each component of head loss decreased with embedment, the exit head loss decreased the most. Total head loss also increased with discharge. These results mean that the culvert exit (or fish entrance) of embedded culverts have reduced velocities and less of a water elevation change compared to culverts installed at grade. A reduction in velocity may help fish enter the culvert. The entrance loss coefficients were calculated and range from 0.75 to 0.97, which is comparable to the published value of 0.9 for culverts projecting from fill (CSPI 2002).

A velocity distribution exists within a culvert barrel causing question as to whether the mean velocity is an appropriate criterion for assessing a fish's ability to swim through a culvert. For this research study, this specific velocity criterion was examined by quantifying the velocity distribution and comparing the distribution between culverts placed at grade and embedded. The streamwise velocity distributions were presented in the form of contour plots. A total of 45 plots were created (i.e. five locations for each of the nine combinations of culvert placement and discharge). Generally, all plots showed good symmetry. The mean velocity in the cross-section decreased as the culvert embedment increased.

DFO recommend that the mean velocity of the flow within a culvert should not exceed the capability of the weakest swimming fish (Katopodis 1992). It has been shown that fish, however, have the natural ability to find the low velocity zones (Behlke et al. 1991; Lang et al. 2004). For this reason, the amount of flow area below the mean velocity of that in the cross-section is of interest. For conditions examined in this research study, when the culvert was placed at grade, on average approximately 44% of the flow area was less than the mean velocity of the flow field. When the culvert was placed at an embedment of $0.1D$ and $0.2D$, on average approximately 70% and 98% of the flow field was less than the mean velocity of the flow field during normal flow conditions.

Being able to predict the velocity distribution within the culvert can be helpful for culvert designs in the context of fish passage. Ead et al. (2000) expanded the Prandtl-von Karman equation for one-dimensional vertical velocity distribution for the rough flow regime (Equation 2.2) to account for non-central velocity predictions. Velocity measurements taken when the culvert was placed at grade during this research study were compared to the results found using the Ead et al. (2000) equations. It was found that the Ead et al. (2000) equations may adequately predict streamwise velocities near the centerline of the culvert. However, they do not appear to predict streamwise velocities near the boundary of the culvert with very good accuracy, and the boundary areas are of the most concern for fish passage.

Observations of fish movement indicate that the zones occupied by fish within a culvert can be relatively localized and not include the full cross-section (House et al. 2005). These observations have led to methods of predicting the percentage of flow area within a cross-section containing velocities less than a given velocity (White 1996, House 2001, House et al. 2005, Magura 2007). The idea is that the extent of the occupied zone can be estimated during the design process. A similar analysis was conducted for this research study. The measured velocity was non-dimensionalized using the mean velocity of the flow field for each particular cross-section. This method of non-dimensionalizing the velocity causes the data to collapse onto one curve, regardless of embedment. Although the spatial distribution of the flow areas was not assessed, it has been shown through observations of the velocity distribution plots that the areas of similar velocity are "clumped" together rather than distributed throughout the cross-section. In other words, a flow area with a certain velocity will likely be located in a contiguous semi-circular ring around the culvert boundary. It will not be spread out in various locations throughout the cross-section. This is significant because the flow area given in the collapsed curve can be assumed to be contiguous instead of scattered about the cross-section, which means that that flow area can be directly related to the size of a target fish species using the culvert.

Since the velocity was measured at such a high frequency using the ADV, the *TI* distribution was also calculated. In general, the *TI* was found to be 0.3 or less, with the majority of the cross-section containing *TI* of approximately 0.1. Increasing the discharge does not change the distribution significantly. Increasing the embedment depth also does not appear to significantly affect the *TI* distribution.

6.2 Conclusions

The aim of this research program was to provide for a better understanding of the hydraulics of embedded culverts. Specifically, this research quantified the velocity distribution found with the culvert under various combinations of culvert placement and discharge by producing velocity contour plots. The hydraulic conditions, including flow depths, velocities and turbulence intensities, found within each combination were compared. It was found that embedding the culvert created an M1 water surface profile for part-full flow conditions. In this research study, the profile extended the entire length of the culvert. However, for other culvert configurations, such as a longer pipe or a different culvert slope, the extent of the M1 profile may not extend through the entire culvert. The water depth may reach normal depth somewhere within the culvert barrel, creating conditions similar to an at-grade culvert installation. In these situations, the M1 profile may help the fish enter the culvert, but may not necessarily improve hydraulic conditions throughout the entire culvert length. An analytical approach can be used to determine if the M1 water surface profile extends throughout the entire length of the culvert or not.

The M1 surface water profile causes an increase in flow depth which in turn causes the velocities within the culvert to decrease. As a result of reduced velocities throughout the length of the culvert, the total head loss was reduced. A reduction in velocity and a reduction in the length of the high velocity region can help fish swim through a culvert.

Although embedding the culvert created a systematically varying mean velocity along the culvert length, on average, embedding the culvert 0.1*D* caused a 15% decrease in the mean velocity, while embedding the culvert 0.2*D* caused a 30% decrease in the mean velocity. This decrease in velocity occurred consistently for all discharges and cross-sections measured along the length of the culvert.

For conditions examined in this research study, when the culvert was placed at grade, on average approximately 44% of the flow area was less than the mean velocity of the flow field. When the culvert was placed at an embedment of 0.1*D* and 0.2*D*, on average approximately 70% and 98% of the flow field was less than the mean velocity of the flow field during normal flow conditions. These results show that for normal flow conditions (i.e., the culvert placed at grade), just less than half of the flow area has a velocity less than the mean. Therefore, in many instances, use of a mean velocity criterion could be excessive in terms of a specification for fish passage. With embedment, the hydraulic conditions for fish passage may be improved, at least from a velocity perspective.

The analysis of the percent of flow area less than a given velocity (i.e., a cumulative frequency distribution of the non-dimensional velocity of flow) generally followed a single relationship, supporting a previous study by Magura (2007) in which it was concluded that predicting flow area at a given velocity may be possible. This trend is significant because the flow area given in the curve may be directly related to the size of a target fish species using the culvert. However, slope effects were not studied in this research.

Some peripheral findings from this research study that are not directly related to the research objectives, but are important include:

- The Manning's n of the research corrugated steel pipe found to be 0.024, which is a well-established value in published literature;
- The entrance loss coefficients were calculated and range from 0.75 to 0.97, which is comparable to the published value of 0.9 for culverts projecting from fill;
- The flow within the culvert was found to be fully developed approximately 3.0 m from the culvert inlet;

- The Ead et al. (2000) velocity distribution prediction equations may adequately predict streamwise velocities near the centerline of the culvert; however, they do not appear to predict streamwise velocities near the boundary of the culvert with very good accuracy; and
- When doing a qualitative comparison of *TI* measured in this research study, generally increasing the discharge or embedment depth did not significantly affect the *TI* distribution.

6.3 Recommendation for Further Research

Based on a review of existing literature and the results of this study, the following recommendations are proposed to provide guidance for future research:

- Continue investigating the hydraulics of embedding culverts, including velocity and turbulence intensity, by varying other hydraulic parameters such as culvert slope;
- Develop a method of predicting the spatial distribution of the low velocity zone within the culvert to determine whether a target fish species can physically fit within the low velocity zones; and
- Continue work on predictive relationships for velocity distributions within a culvert.

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APPENDIX A

Determination of Manning's n for the Model Culvert

To find the value of Manning's *n* for the 500 mm diameter model culvert, measurements were taken at a location five meters from the culvert inlet (i.e. Hole 9). The tailwater was set to normal depth by adjusting the vertical leaf tailgate, and the culvert slope was set to approximately 0.5%. Table A.1 lists the recorded pump frequency and flow meter reading, as well as the measured flow depths and corresponding calculated flow characteristics.

Table A.1 Summary of measurements taken and values calculated for hydraulic resistance analysis.

Pump Frequency (Hz)	Flow Meter (V)	Flow Depth (m)	Discharge (m^3/s)	Flow Area (m^2)	Hydraulic Radius (m)	Culvert Slope (m/m)	$AR_h^{2/3}S^{1/2}$
14.0	0.85	0.172	0.035	0.06	0.096	0.005	0.0009
19.0	1.16	0.194	0.047	0.07	0.105	0.005	0.0011
23.0	1.41	0.221	0.057	0.08	0.115	0.005	0.0014
28.0	1.76	0.241	0.071	0.09	0.122	0.005	0.0016
31.5	2.02	0.266	0.081	0.11	0.130	0.005	0.0019
34.0	2.18	0.274	0.087	0.11	0.132	0.005	0.0020
29.5	1.88	0.259	0.076	0.10	0.128	0.005	0.0018
26.0	1.64	0.244	0.066	0.10	0.123	0.005	0.0017
24.5	1.55	0.235	0.062	0.09	0.120	0.005	0.0016
22.0	1.39	0.219	0.056	0.08	0.115	0.005	0.0014
20.0	1.24	0.213	0.050	0.08	0.112	0.005	0.0013
17.5	1.08	0.197	0.044	0.07	0.106	0.005	0.0011
16.0	0.99	0.189	0.040	0.07	0.103	0.005	0.0011
15.0	0.91	0.179	0.037	0.06	0.099	0.005	0.0010

Notes: Hz = Hertz, V = volts, m = metres, and *S* = slope

The flow in the culvert was uniform flow and thus n could be determined by simple application of Manning's equation (Equation 4.1 of the main thesis document); therefore, the flow depth at every culvert access hole was the same. For this analysis, Hole 9 was used.

Values of $AR_h^{2/3}S^{1/2}$ were plotted against the discharge, as shown in Figure A.1, where A is the cross-section flow area, R_h is the hydraulic radius and S is the slope. A linear line was drawn through the data points with a forced zero intercept. The slope of the line gave the value of 0.024 for Manning's n with a correlation coefficient of 0.97. A value of 0.024 is in agreement with commonly published values for annular corrugated steel pipe (e.g., CSPI 2002).

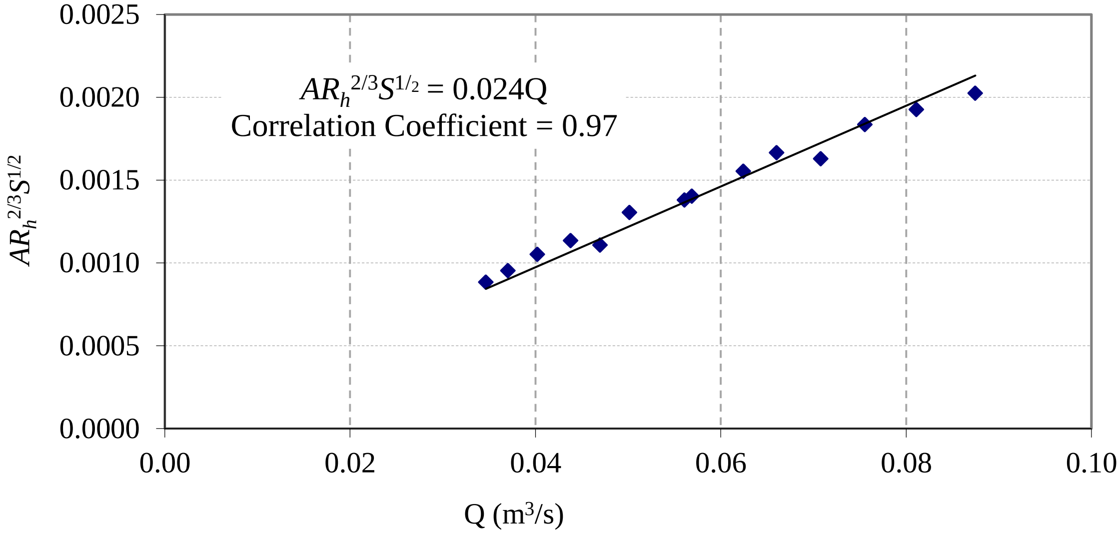

Figure A.1 Relationship used in determining Manning's resistance coefficient, n.

APPENDIX B
Flow Meter Calibration

B.1 Introduction

The magnetic flow meter did not have a digital discharge reading. Instead, a volt meter was attached to the magnetic flow meter and the voltage reading was recorded. From the recorded value, the discharge could be determined using an existing calibration curve. Verification of the existing calibration curve was required, especially in the lower flow region. V-notch and rectangular sharp-crested weirs were chosen to measure the range of possible flow rates in the flume. The two weirs were used so that the entire range of flows that were possible in the flume could be tested. With knowledge of the head on the weir crest and the weir geometry, the corresponding discharge could be determined from previously established head-discharge relationships.

A V-notch sharp-crested weir was used to test heads ranging from 0.06 m to 0.28 m. These heads correspond to discharges ranging from approximately 1.5 L/s to 56.5 L/s. The crest of the V-notch was set 0.30 m above the flume bed. The rectangular sharp-crested weir was used to test heads ranging from 0.02 m to 0.16 m. These heads correspond to discharges ranging from approximately 25 L/s to 150 L/s. The pump capacity was 60 Hz which produced approximately 157 L/s.

B.2 Experiment

Tests were conducted in the University of Saskatchewan's Hydrotechnical Laboratory. The V-notch and rectangular sharp-crested weirs were secured into the flume approximately 3.15 m upstream of the tailgate. A voltage meter was attached to the magnetic flow meter to display the voltage across the flow meter corresponding to a certain discharge. The experimental setup and instrumentation are shown in Figure B.1.

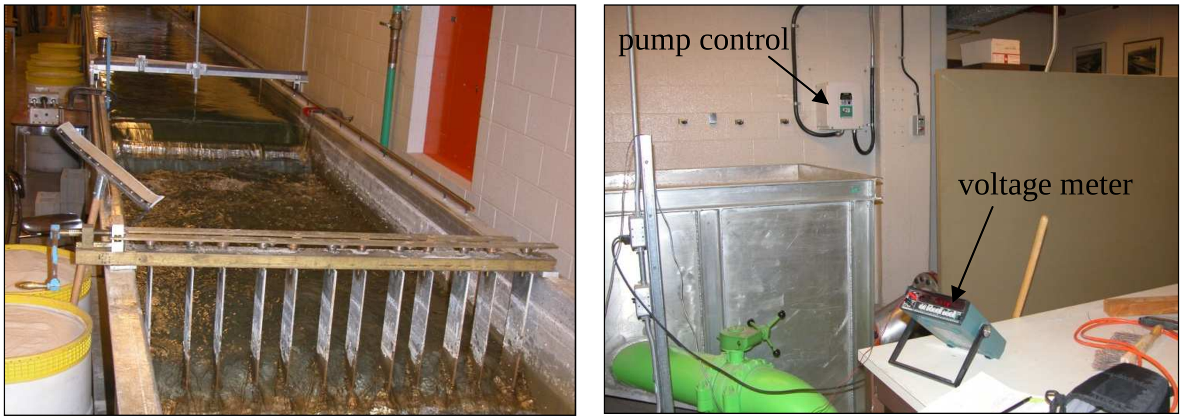

Figure B.1 Experimental setup and instrumentation.

The pump rotation speed, the voltage across the magnetic flow meter, and the head on the weir were recorded. The head on the weir was measured using a point gauge at a location upstream of the weir equal to or slightly greater than three times the head on the weir, which was beyond the drawdown zone.

Twelve tests were conducted for the V-notch sharp-crested weir. Figure B.2 are photographs of the V-notch sharp-crested weir with low and high flows. Table B.1 presents the data collected for these tests. The tests were done with no submergence.

Fourteen tests were conducted for the rectangular sharp-crested weir. Figure B.3 are photographs of the rectangular sharp-crested weir with low and high flows. Table B.2 presents the data collected for these tests. The rectangular sharp-crested weir can tolerate no submergence.

Figure B.2 V-notch sharp-crested weir at low flow and high flow.

Table B.1 V-notch sharp-crested weir data.

Test	Head (cm)	Flow Meter (V)	Pump (Hz)	C_d	Discharge (L/s)
1	6.68	0.017	4.5	0.60	1.63
2	8.00	0.039	5.5	0.60	2.57
3	10.20	0.090	7.0	0.59	4.63
4	12.44	0.163	8.5	0.59	7.61
5	14.92	0.274	9.0	0.58	11.78
6	16.86	0.383	10.8	0.58	15.99
7	18.78	0.510	11.5	0.58	20.94
8	20.34	0.625	13.3	0.58	25.57
9	22.09	0.776	14.5	0.58	31.42
10	23.90	0.945	17.0	0.58	38.26
11	25.10	1.077	19.0	0.58	43.25
12	27.30	1.330	22.0	0.58	53.36

Notes: cm = centimeters, V = volts, Hz = hertz and C_d = weir coefficient (Smith 1995)

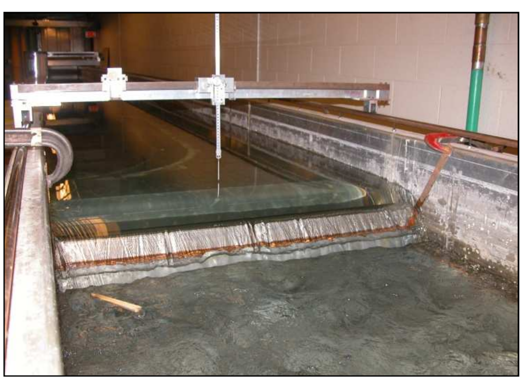

Figure B.3 Rectangular sharp-crested weir at low flow and high flow.

Table B.2 Rectangular sharp-crested weir data.

Test	Head (cm)	Flow Meter (V)	Pump (Hz)	C_d	Discharge (L/s)
13	5.24	0.651	12.0	1.88	27.04
14	5.98	0.790	14.0	1.88	32.93
15	6.76	0.967	16.5	1.88	39.56
16	7.86	1.204	19.0	1.88	49.64
17	9.14	1.545	24.0	1.88	62.36
18	9.90	1.827	28.0	1.88	70.39
19	11.32	2.15	32.5	1.89	86.34
20	11.96	2.32	35.0	1.89	93.91
21	12.56	2.54	38.5	1.89	101.21
22	13.30	2.77	41.5	1.90	110.50
23	14.04	3.00	45.0	1.90	120.09
24	15.10	3.33	50.0	1.91	134.35
25	16.14	3.70	55.0	1.91	148.91
26	16.96	4.04	60.0	1.92	160.79

Notes: cm = centimeters, V = volts, Hz = hertz and C_d = weir coefficient

B.3 Discharge and Magnetic Flow Meter Relationship

The relationship between the discharge and the voltage across the magnetic flow meter was plotted for the V-notch and rectangular sharp-crested weirs, as shown in Figure B.4. Separate trend lines were fitted to the V-notch and rectangular sharp-crested weir data. It can be seen that there is a linear relationship with only a slight difference between the two weirs. The slopes of the trend lines for the rectangular and V-notch weirs are 0.0397 and 0.0393, respectively. The rectangular sharp-crested weir is 1% greater than the V-notch. Both trend lines were not forced through the origin because of the residual voltage readings of -0.023V and -0.026V for the rectangular and V-notch weirs, respectively. When combining the V-notch and the sharp-crested weir data, the slope of the trend line became 0.040, as shown in Figure B.5.

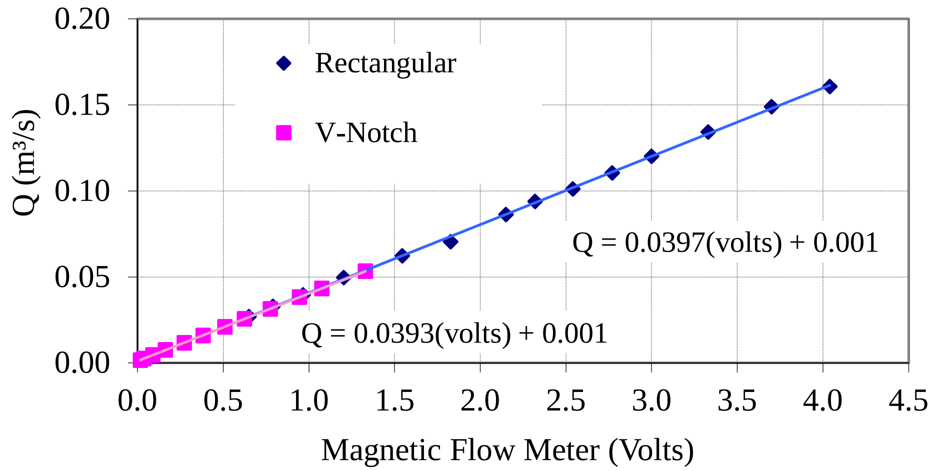

Figure B.4 Flow calibration curve showing results from both weirs.

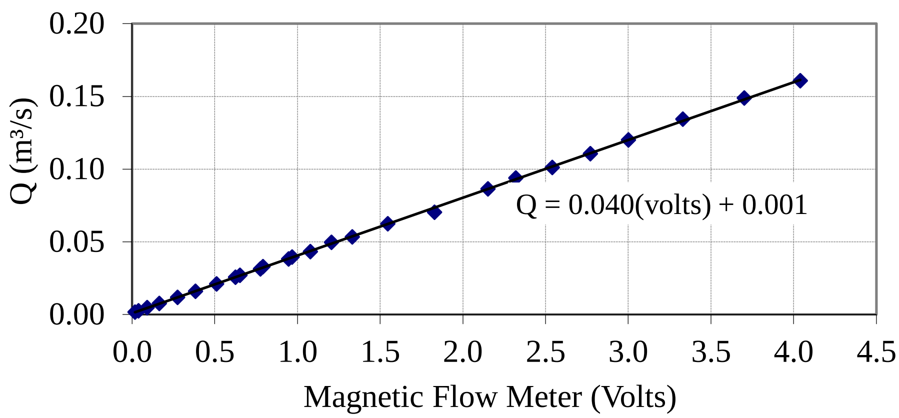

Figure B.5 Flow calibration curve showing combined results.

B.4 Conclusion

A flow calibration curve was created that related the discharge to the magnetic flow meter voltage using both rectangular and V-notch sharp-crested weirs. A linear relationship was found to be $Q = 0.040(volts) + 0.001$ where Q is the discharge in m^3/s and the volts is the voltage across the magnetic flow meter. This relationship is in agreement with previous calibration curves for this magnetic flow meter setup. The trend line was not forced through the origin due to a residual voltage reading.

APPENDIX C
ADV Sampling Time Analysis

C.1 Introduction

The accuracy of the calculated mean velocities and RMSs are affected by the ADV sampling duration. Choosing a long sampling duration will provide enough samples that, when averaged, will converge towards the true mean velocity values. However, it has implications in terms of the time it takes to carry out a test.

C.2 ADV Operations

Before looking at the data collected that may indicate the sampling duration required for the model study, it is important to understand the uncertainty of the ADV operation.

There are two main factors that add to the uncertainty of the velocity data: noise and probe geometry. Under good operating conditions (i.e. SNR>15 dB and the CORR>70%), the noise in ADV horizontal velocity data is estimated at 1% of the velocity range when outputting at 25 Hz. For example, individual samples at 25 Hz will have horizontal noise of about ±1 cm/s if using the ±100 cm/s velocity range. As mentioned previously, noise decreases with the square root of the sampling rate; thus, individual samples at 50 Hz would have noise of about ±1.4 cm/s when using the ±100 cm/s velocity range. Noise in horizontal velocity (*x*-velocity) measurements is larger than in vertical velocity (*z*-velocity) measurements by about a factor of four because the axis of the ADV receivers is 15 degrees off the vertical axis. Probe geometry is calibrated at the factory for each ADV, and the accuracy of the geometry is specified to ±1.0% of the measured velocity. Sound speed also affects the accuracy of the velocity measurements; however, errors associated with sound speed are typically very small and can be corrected in post-processing.

C.3 Experiment

To determine the required sampling duration, the ADV was used to collect velocity data for various flow conditions within the culvert. Several sampling durations were investigated. The ADV was inserted into the desired access hole and positioned along the culvert centerline (i.e. the ADV was not tilted).

Table C.1 outlines the combination of tests that were conducted to determine the sampling duration. Each test ran for 20 minutes.

Table C.1 Test conducted in culvert to determine sampling duration

Test	Discharge (m^3/s)	Distance from invert (cm)	Distance from inlet (m)	Velocity range (cm/s)	Water Temperature (^oC)
1	0.02	7.8	0.25	±100	11
2	0.02	5.0	0.25	±100	11
3	0.02	2.1	0.25	±100	11
4	0.04	7.8	0.25	±100	11
5	0.04	5.0	0.25	±100	11
6	0.04	2.1	0.25	±100	11
7	0.02	6.0	3	±100	17
8	0.02	3.0	3	±100	17
9	0.02	0.6	3	±100	17
10	0.04	6.0	3	±100	17
11	0.04	3.0	3	±100	17
12	0.04	0.6	3	±100	17

To filter and analyze the data, each test file was opened in WinADV. The following filter criteria were used:

- The average sound-to-noise ratio (SNR) was greater than 70; and
- The average correlation score (CORR) was greater than 15.

WinADV has the ability to analyze specified sections of each file. Therefore, to determine the required sampling duration, the first minute, then the first two minutes, then the first three minutes, to the first 10 minutes of each file were analyzed. In other words, ten sections of the data were sampled, with each a different duration all starting from time equals zero. For each specified sampling section, WinADV calculated the mean x, y, and z velocities and corresponding RMS values using only the filtered data.

C.4 Results

Figures C.1 to C.3 show the mean *x*-velocity results of Tests 1 to 12. The results are split into three graphs to accommodate the *y*-axis scaling. The *y*-velocity results are shown in Figures C.4 and C.5. The *z*-velocity results are shown in Figures C.6 and C.7. It is important to note that the scales of the velocity graphs vary.

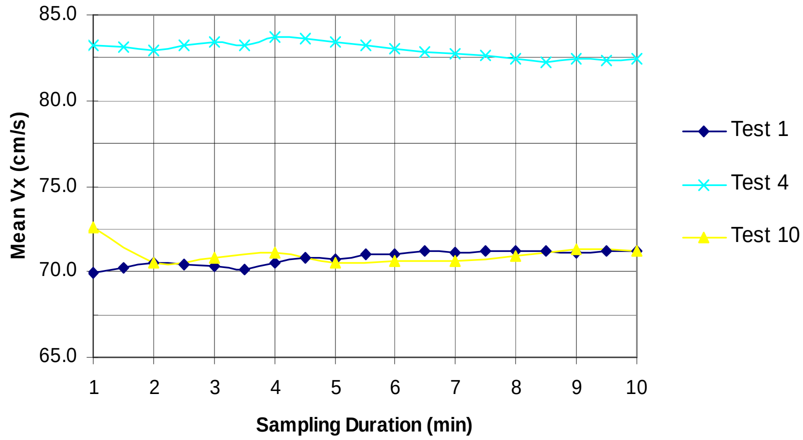

Figure C.1 Mean *x*-velocity versus sampling duration of highest velocities.

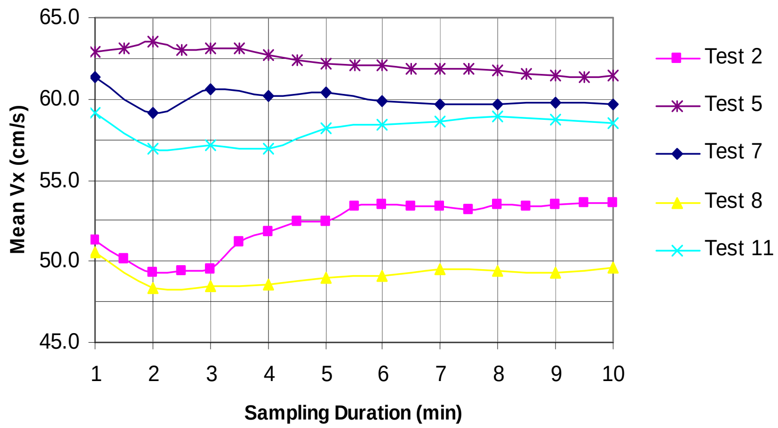

Figure C.2 Mean *x*-velocity versus sampling duration of middle velocities

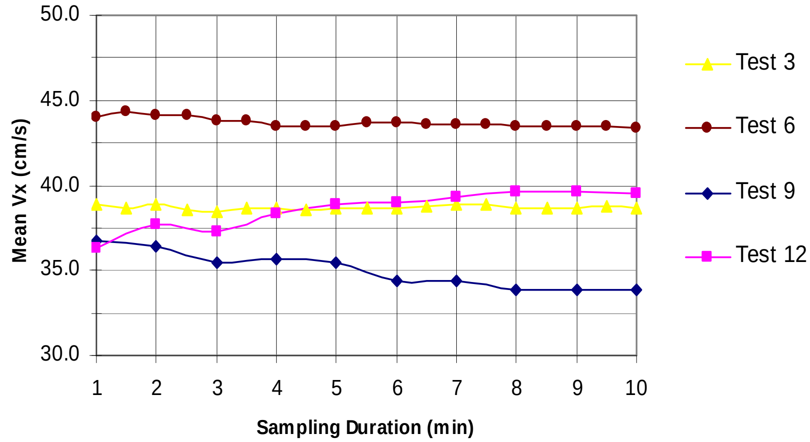

Figure C.3 Mean *x*-velocity versus sampling duration of lower velocities.

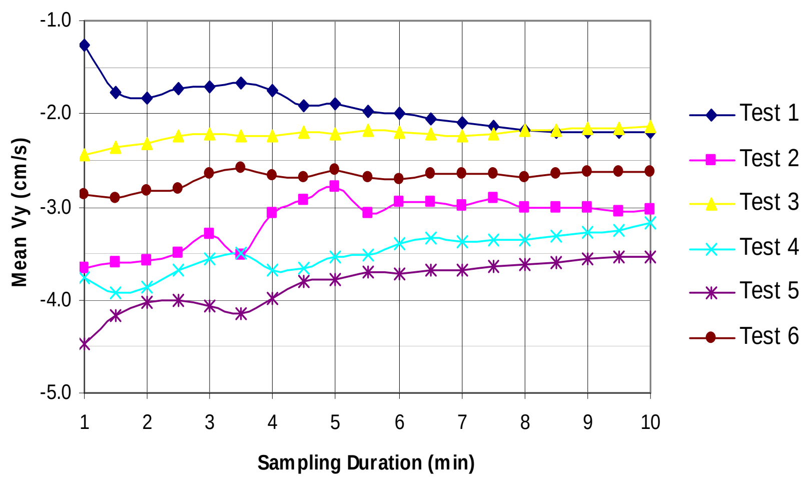

Figure C.4 Mean *y*-velocity versus the sampling duration for Tests 1 to 6.

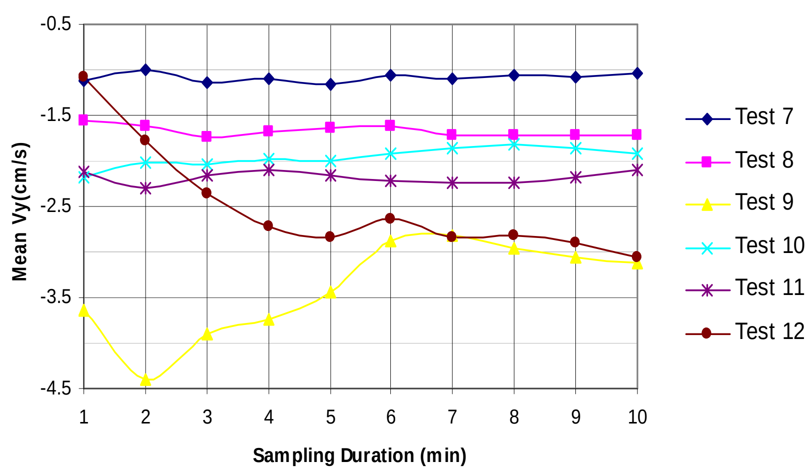

Figure C.5 Mean *y*-velocity versus the sampling duration for Tests 7 to 12.

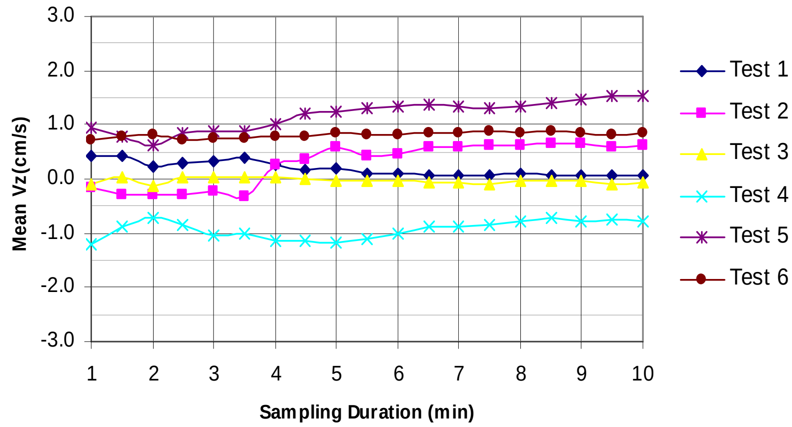

Figure C.6 Mean *z*-velocity versus sampling duration for Tests 1 to 6.

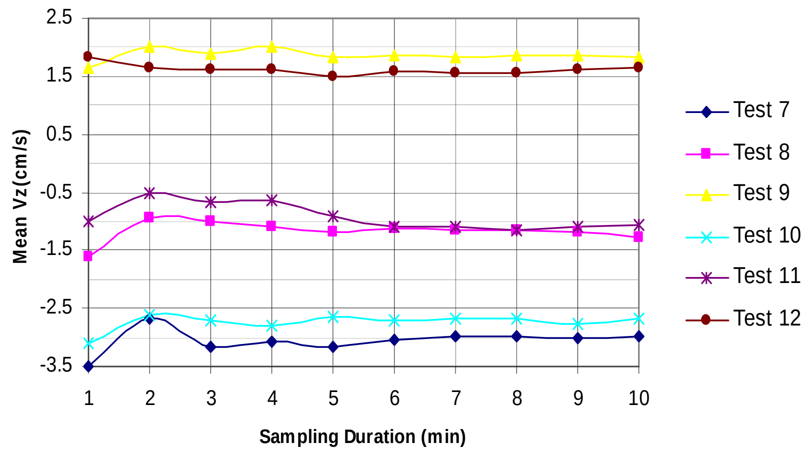

Figure C.7 Mean *z*-velocity versus sampling duration for Tests 7 to 12.

Figures C.8 and C.9 show the RMS for the *x*-velocity results of Tests 1 to 12. Figures C.10 and C.11 show the RMS for the *y*-velocity results of Tests 1 to 12. Figures C.12 and C.13 show the RMS for the *z*-velocity results of Tests 1 to 12.

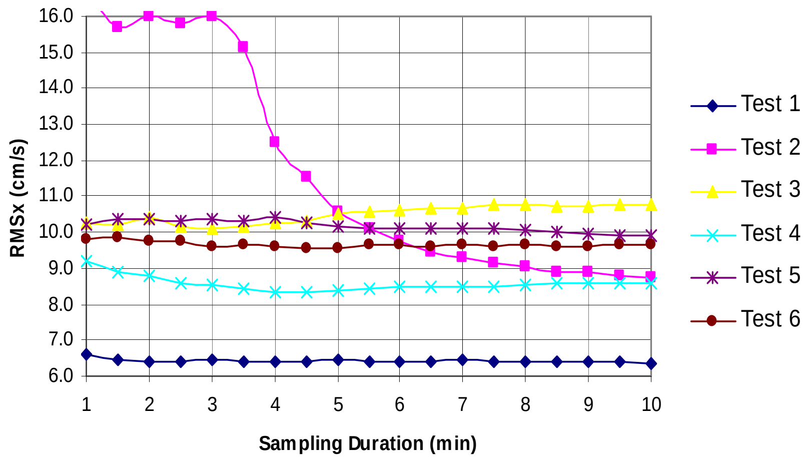

Figure C.8 RMS in the *x*-direction versus sampling duration for Tests 1 to 6.

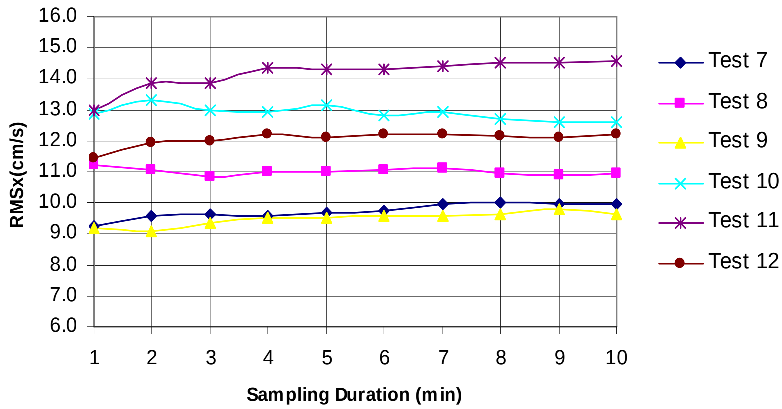

Figure C.9 RMS in the *x*-direction versus sampling duration for Tests 7 to 12.

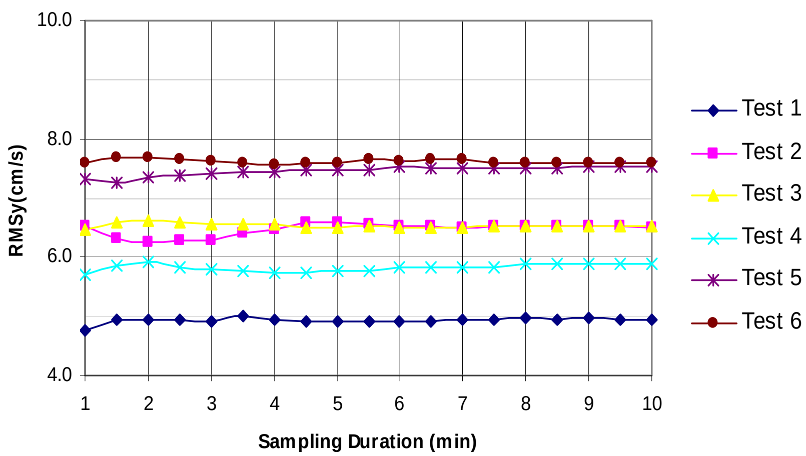

Figure C.10 RMS in the *y*-direction versus sampling duration for Tests 1 to 6.

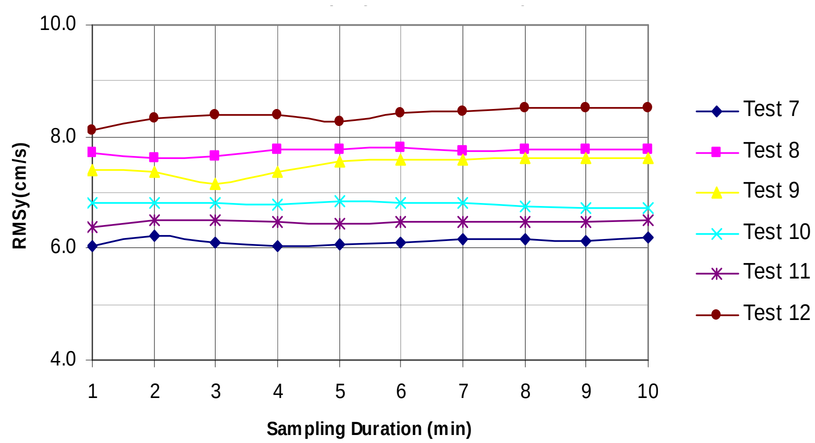

Figure C.11RMS in the *y*-direction versus sampling duration for Tests 7 to 12.

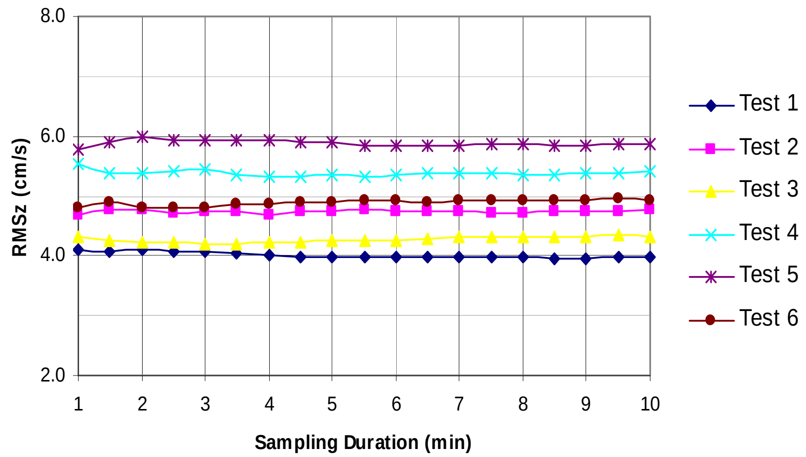

Figure C.12 RMS in the *z*-direction versus sampling duration for tests 1 to 6.

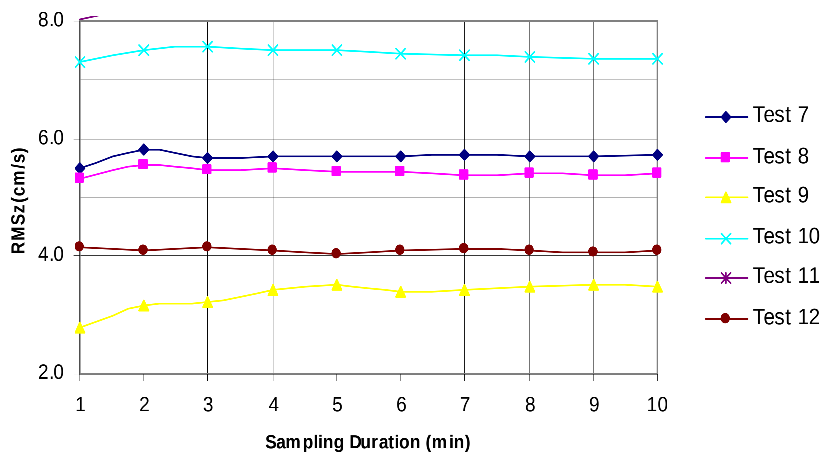

Figure C.13 RMS in the *z*-direction versus sampling duration for tests 7 to 12.

C.5 Conclusions

From the data collected, it appears that the required sampling durations is approximately four to five minutes before the mean velocities become constant and three to four minutes before the RMS become constant. However, some tests found that it took the full 10 minutes to arrive at a constant mean velocity; therefore, it was decided that a sampling duration of 10 minutes would be used.

APPENDIX D

Water Survey Profile Data

Table D.1 Water depth in cm as measured by a point gage for each combination of culvert placement and discharge.

Hole	x (m)	-------------50 L/s-------------			-------------70 L/s-------------			-------------90 L/s-------------		
		At-Grade	0.1*D*	0.2*D*	At-Grade	0.1*D*	0.2*D*	At-Grade	0.1*D*	0.2*D*
upstream	-0.8	n/a	22.24	24.26	n/a	27.20	28.40	30.74	31.86	33.92
upstream	-0.3	21.32	22.02	23.74	25.74	26.86	28.26	30.12	31.60	33.56
1	0.3	17.26	20.58	23.72	20.04	23.04	26.72	23.26	26.46	30.52
2	0.5	19.26	20.28	24.04	23.46	25.86	26.66	26.10	29.52	31.24
3	0.7	19.60	21.26	24.52	22.64	25.04	28.16	26.82	29.20	33.16
4	1.0	18.48	21.82	24.88	23.00	24.48	27.64	26.78	29.00	32.34
5	1.5	18.60	21.26	25.50	22.76	24.28	28.68	26.78	28.86	33.32
6	2.0	19.60	21.22	26.02	22.70	24.24	29.48	26.60	28.76	33.28
7	3.0	19.84	21.38	26.86	23.12	25.68	30.30	26.62	28.82	33.88
8	4.0	18.50	21.74	27.60	22.76	25.60	30.80	26.40	28.80	35.00
9	5.0	19.48	23.20	28.64	23.32	25.86	31.38	27.18	29.98	35.68
10	6.0	19.14	23.28	28.56	22.84	26.06	31.72	26.56	29.62	35.68
11	6.5	19.22	23.46	28.68	22.96	26.06	31.62	26.86	29.98	35.56
12	7.0	19.10	23.60	28.68	22.86	26.16	31.54	26.54	30.48	35.86
13	7.3	19.00	23.88	28.60	22.96	26.62	31.68	26.52	30.50	35.52
14	7.5	18.88	23.94	28.60	22.48	26.86	31.40	26.38	30.50	35.38
15	7.7	18.38	23.66	28.18	21.84	27.06	31.06	25.56	30.08	34.62
outlet	8.0	n/a	24.14	27.66	n/a	26.92	31.04	25.46	30.56	34.28
downstream	8.8	n/a	24.14	27.76	n/a	27.00	31.14	25.98	30.84	33.48

Notes: cm = centimetres, n/a = not available, 0.1*D* and 0.2*D* = an embedment of 0.1 or 0.2 times the culvert diameter

APPENDIX E

Vertical Velocity Data

The following tables present the streamwise velocity measured at a certain vertical distance from the invert at the culvert centerline for various *x*-locations along the length of the culvert.

Table E.1 Culvert Placed at Grade with a Discharge of 50 L/s.

Hole	x (m)	z (m)	% good samples	u (cm/s)
1	0.25	2.6	16.4	82.9
		3.6	99.6	88.7
		5.6	15.4	91.5
		7.6	99.4	93.2
		9.6	96.0	95.3
		11.6	86.4	97.6
2	0.50	0.6	0.0	55.8
		2.6	98.9	80.8
		4.6	99.0	89.9
		6.6	71.6	90.6
		8.6	98.7	92.0
		10.6	98.8	91.6
		11.6	98.5	91.2
		14.6	98.0	91.9
4	1.00	1.1	0.0	76.0
		3.1	95.6	81.1
		5.1	94.7	92.0
		7.1	65.8	91.6
		9.1	98.0	96.0
		11.1	85.5	95.3
5	1.50	4.6	54.0	88.4
		6.6	2.7	97.0
		8.6	75.7	98.7
		10.6	97.2	99.6
		12.6	14.3	97.8
6	2.00	0.6	91.1	61.4
		1.1	96.8	65.7
		3.1	97.0	78.4
		5.1	81.2	87.5
		7.1	92.2	94.0
		9.1	95.2	97.5
		11.1	95.2	97.9
		13.1	84.7	97.0
7	3.00	0.6	57.9	40.3
		1.6	66.2	62.1
		3.6	52.2	75.5
		5.6	93.6	87.2
		7.6	57.1	91.4
		9.6	95.1	96.8
		11.6	96.3	99.7
		13.6	75.1	98.3
8	4.00	0.6	0.4	51.1
		2.6	0.3	67.0
		4.6	90.4	85.0
		6.6	27.8	91.7
		8.6	94.5	102.4
		10.6	96.6	104.0
		12.6	26.1	97.3
9	5.00	0.6	17.8	46.3
		1.6	62.5	64.0
		3.6	59.9	78.4
		5.6	0.3	83.8
		7.6	1.5	96.1
		9.6	95.3	100.4
		11.6	95.2	100.0
		13.6	84.3	97.0
11	6.50	4.6	74.0	88.5
		6.6	3.1	95.3
		8.6	51.5	98.6
		10.6	82.9	97.3
		12.6	28.1	94.0
14	7.50	0.6	76.3	62.6
		2.6	80.0	74.2
		4.6	94.3	87.8
		6.6	83.5	94.0
		8.6	96.7	97.0
		10.6	98.0	96.4
		12.6	87.3	92.7

Table E.2 Culvert Placed at Grade with a Discharge of 70 L/s.

Hole	x (m)	z (m)	% good samples	u (cm/s)
1	0.25	1.6	85.2	98.9
		3.6	97.4	98.1
		5.6	99.6	101.4
		7.6	99.2	103.0
		9.6	99.1	104.7
		11.6	90.4	106.2
2	0.50	0.6	0.0	-5.6
		2.6	0.0	79.0
		4.6	99.1	92.2
		6.6	97.6	101.5
		8.6	99.2	103.4
		10.6	99.1	103.5
		12.6	97.7	103.1
		14.6	94.9	102.1
4	1.00	1.6	88.4	63.2
		2.1	99.8	67.6
		3.6	99.6	79.7
		5.6	98.6	92.2
		7.6	97.3	99.4
		9.6	98.6	101.6
		11.6	97.0	101.8
		13.6	95.1	101.1
		15.6	69.8	95.1
5	1.50	4.6	98.1	94.1
		6.6	97.5	100.9
		8.6	97.5	104.7
		10.6	97.6	106.5
		12.6	98.4	106.0
		14.6	97.9	104.7
6	2.00	2.6	57.0	64.1
		3.6	99.6	69.5
		5.6	99.6	81.5
		7.6	99.4	91.3
		9.6	98.2	99.6
		11.6	98.2	103.7
		13.6	99.1	104.8
		15.6	12.8	95.6
7	3.00	3.1	77.6	68.0
		3.6	99.6	70.0
		5.6	99.6	77.3
		7.6	99.5	86.4
		9.6	99.0	94.1
		11.6	98.0	100.4
		13.6	97.7	104.3
		15.6	64.1	102.0
8	4.00	2.6	73.6	71.8
		4.6	99.0	81.2
		6.6	99.1	89.7
		8.6	99.1	98.2
		10.6	98.5	103.5
		12.6	98.2	108.3
		14.6	84.6	108.4
9	5.00	1.6	1.0	65.7
		3.1	99.7	71.9
		4.1	99.6	74.9
		6.1	99.4	83.6
		8.1	99.2	91.0
		10.1	98.9	96.6
		12.1	97.9	101.2
		14.1	98.4	102.7
		16.1	74.7	99.8
11	6.50	4.6	93.4	84.2
		6.6	97.3	94.3
		8.6	97.6	99.2
		10.6	97.5	103.9
		12.6	97.7	104.6
		14.6	98.4	102.3
14	7.50	0.6	2.7	44.7
		2.6	50.1	80.2
		4.6	99.2	90.6
		6.6	98.8	98.4
		8.6	97.8	104.9
		14.6	87.7	105.6
		12.6	98.4	107.0
		10.6	97.7	107.0

Table E.3 Culvert Placed at Grade with a Discharge of 90 L/s.

Hole	x (m)	z (m)	% good samples	u (cm/s)
1	0.25	4.6	93.58	106.2
		6.6	93.35	108.4
		8.6	93.65	110.5
		10.6	93.47	112.3
		12.6	94.08	113.9
		14.6	90.46	115.0
2	0.50	2.6	0.68	95.9
		4.6	97.14	104.9
		6.6	97.54	107.3
		8.6	91.56	108.8
		10.6	97.06	110.4
		12.6	90.86	110.7
		14.6	95.09	111.1
		16.6	80.46	110.3
		18.6	52.27	108.0
4	1.00	0.6	0.58	54.1
		2.6	56.45	80.9
		4.6	97.26	91.4
		6.6	96.26	100.5
		8.6	95.28	107.3
		10.6	93.78	111.0
		12.6	92.88	112.1
		14.6	93.57	111.0
		16.6	95.30	105.8
		18.6	96.05	97.1
		20.6	89.62	87.4
5	1.50	2.6	2.34	76.4
		4.6	95.43	80.0
		6.6	96.59	89.8
		8.6	96.35	98.8
		10.6	96.28	105.3
		12.6	95.76	109.5
		14.6	97.09	109.7
		16.6	99.29	101.9
		18.6	99.45	95.3
6	2.00	2.6	0.87	64.6
		4.6	98.76	76.6
		6.6	99.13	85.9
		8.6	99.18	94.3
		10.6	98.89	102.0
		12.6	98.80	107.0
		14.6	99.23	106.6
		16.6	99.49	103.5
		18.6	97.53	98.9
		20.6	88.73	94.1

Hole	x (m)	z (m)	% good samples	u (cm/s)
7	3.00	2.6	17.05	62.2
		4.6	98.50	76.7
		6.6	98.57	83.5
		8.6	99.16	89.4
		10.6	99.17	95.9
		12.6	99.00	101.3
		14.6	98.97	103.1
		16.6	99.14	103.2
		18.6	99.12	101.1
		20.6	74.32	96.3
8	4.00	2.6	72.83	68.7
		4.6	98.71	77.4
		6.6	98.93	83.0
		8.6	99.21	89.3
		10.6	98.44	95.7
		12.6	98.08	101.2
		14.6	98.49	104.0
		16.6	98.38	106.3
		18.6	80.50	104.6
9	5.00	1.1	88.45	60.5
		3.1	96.02	73.8
		5.1	9.24	80.1
		7.1	83.61	87.0
		9.1	95.12	92.6
		11.1	95.38	97.8
		13.1	95.57	101.6
		15.1	96.29	104.1
		17.1	97.32	104.0
		19.1	94.22	101.6
		21.1	82.61	97.7
11	6.50	4.6	99.33	87.0
		6.6	99.38	93.4
		8.6	98.60	100.9
		10.6	98.65	105.5
		12.6	97.65	109.3
		14.6	98.16	109.8
		16.6	98.78	110.4
		18.1	86.58	107.4
14	7.50	2.6	1.86	83.3
		4.6	98.81	92.7
		6.6	98.44	101.4
		8.6	98.34	107.1
		10.6	97.81	111.4
		12.6	97.99	113.3
		14.6	98.70	113.2
		16.6	99.18	112.3
		18.6	69.11	109.3

Table E.4 Culvert Placed at an Embedment of 0.1*D* with a Discharge of 50 L/s.

Hole	x (m)	z (m)	% good samples	u (cm/s)
1	0.25	2.1	90.76	64.13
		4.1	99.19	68.59
		6.1	7.83	71.74
		8.1	97.53	74.89
		10.1	96.14	76.72
		12.1	97.64	76.85
		14.1	98.03	77.04
2	0.50	2.6	85.39	58.64
		4.6	98.81	64.51
		6.6	72.76	68.12
		8.6	93.69	72.82
		10.6	62.12	76.37
		12.6	73.81	77.82
		14.6	17.53	78.49
4	1.00	1.6	80.85	59.26
		3.6	95.58	68.29
		5.6	18.28	74.30
		7.1	74.70	75.07
		8.6	94.32	77.26
		10.6	97.10	78.43
		12.6	97.43	78.61
		14.6	97.54	77.71
5	1.50	4.6	80.12	70.71
		8.6	91.31	80.74
		10.6	91.46	82.55
		12.6	93.93	82.55
		14.6	96.10	81.80
6	2.00	3.1	94.33	61.66
		4.6	94.79	68.34
		6.6	32.46	74.73
		8.6	93.19	79.23
		10.6	91.06	81.34
		12.6	93.31	83.29
		14.6	84.32	83.34
		15.6	28.73	79.98
7	3.00	3.6	24.67	56.31
		4.6	96.03	62.54
		6.6	40.81	69.32
		8.6	46.92	73.31
		10.6	93.84	80.50
		12.6	95.21	81.83
		14.6	97.06	80.70
		16.6	90.25	77.88
8	4.00	2.6	94.01	58.64
		4.6	89.73	66.20
		8.6	96.34	75.05
		10.6	96.26	79.14
		12.6	97.23	80.84
		14.6	98.29	80.21
9	5.00	2.6	42.70	52.17
		4.6	94.11	62.54
		6.6	63.43	69.36
		8.6	96.57	73.07
		10.6	95.72	75.84
		12.6	97.62	77.16
		14.6	98.21	75.96
		16.6	98.34	73.69
11	6.50	2.6	82.68	55.70
		4.6	88.46	63.35
		8.6	96.61	72.94
		10.6	96.81	75.78
		12.6	97.31	75.49
		14.6	98.65	74.21
14	7.50	2.6	96.23	57.25
		4.6	92.97	63.93
		6.6	24.99	68.82
		8.6	96.65	72.17
		10.6	97.21	73.76
		12.6	98.30	73.41
		14.6	98.39	71.49

Table E.5 Culvert Placed at an Embedment of 0.1*D* with a Discharge of 70 L/s.

Hole	x (m)	z (m)	% good samples	u (cm/s)
1	0.25	2.6	92.78	76.97
		4.6	92.73	80.48
		6.6	93.74	82.25
		8.6	93.52	85.05
		10.6	94.41	88.43
		12.6	96.05	90.95
		14.6	80.97	91.06
2	0.50	4.6	98.28	77.33
		6.6	98.72	79.15
		8.6	98.16	82.28
		10.6	97.39	85.12
		12.6	97.16	86.52
		14.6	97.23	86.77
		17.6	90.54	84.15
4	1.00	2.6	94.60	56.78
		4.6	95.89	67.88
		6.6	96.96	74.34
		8.6	97.23	77.66
		10.6	97.58	80.16
		12.6	97.69	82.76
		14.6	97.88	84.64
		16.6	98.24	85.37
		17.6	46.11	82.88
5	1.50	2.6	1.63	62.38
		4.6	91.68	73.14
		6.6	91.84	78.19
		8.6	92.20	82.98
		10.6	92.69	87.31
		12.6	91.83	90.01
		14.6	92.77	91.79
		16.6	68.23	92.22
6	2.00	2.6	88.54	55.49
		4.6	98.72	62.79
		6.6	98.91	69.83
		8.6	99.11	76.03
		10.6	98.79	81.62
		12.6	99.22	85.31
		14.6	99.16	88.61
		16.6	87.93	90.03

Hole	x (m)	z (m)	% good samples	u (cm/s)
7	3.00	2.6	37.45	55.72
		4.6	94.96	62.38
		6.6	96.11	68.96
		8.6	96.94	76.04
		10.6	97.65	80.27
		12.6	98.10	84.79
		14.6	98.42	87.52
		16.6	98.47	89.02
		18.6	88.29	88.36
8	4.00	2.6	68.36	61.87
		4.6	94.69	69.99
		6.6	95.80	75.18
		8.6	96.20	82.45
		10.6	96.96	87.72
		12.6	96.47	91.90
		14.6	97.05	94.88
9	5.00	2.6	84.81	54.70
		4.6	97.36	60.79
		6.6	98.21	68.96
		8.6	98.36	71.65
		10.6	98.63	77.60
		12.6	98.74	82.21
		14.6	98.69	85.44
		16.6	98.97	86.70
		19.6	77.61	82.21
11	6.50	2.6	98.11	59.58
		4.6	98.29	66.59
		6.6	98.76	73.28
		8.6	96.32	77.47
		10.6	94.67	80.65
		12.6	95.40	85.90
		14.6	96.37	86.97
		17.6	98.58	86.37
		20.1	87.90	82.86
14	7.50	2.6	97.02	62.56
		4.6	97.73	69.34
		6.6	98.28	75.38
		8.6	97.91	79.99
		10.6	98.12	82.90
		12.6	98.21	84.98
		14.6	89.82	84.18
		17.6	96.83	82.82
		19.6	90.70	79.68

Table E.6 Culvert Placed at an Embedment of 0.1*D* with a Discharge of 90 L/s.

Hole	x (m)	z (m)	% good samples	u (cm/s)
1	0.25	2.6	97.22	86.25
		4.6	95.40	90.28
		6.6	94.79	91.86
		8.6	94.34	93.79
		10.6	94.30	96.19
		12.6	94.38	98.21
		14.6	94.61	100.10
		16.6	96.01	101.40
		18.6	63.74	101.41
2	0.50	2.6	86.77	78.84
		4.6	89.43	83.80
		6.6	91.89	85.34
		8.6	93.37	86.21
		10.6	95.30	87.98
		12.6	96.54	90.02
		14.6	97.78	90.64
		17.1	83.18	89.38
		19.1	86.34	88.23
		21.1	82.38	86.87
4	1.00	1.1	63.70	61.84
		2.6	98.41	69.18
		4.6	98.72	74.66
		6.6	98.56	78.82
		8.6	98.75	81.02
		10.6	98.95	82.73
		12.6	98.72	84.87
		14.6	98.32	87.00
		16.6	96.77	88.73
		18.6	97.28	89.10
		20.6	97.09	86.01
5	1.50	4.6	94.75	74.59
		6.6	8.53	79.74
		8.6	97.73	82.86
		10.6	98.21	85.72
		12.6	98.28	88.53
		14.6	98.01	91.14
		17.1	95.01	93.80
		19.1	96.19	94.59
		21.1	60.87	92.90
6	2.00	2.6	58.37	62.29
		4.6	92.90	68.81
		6.6	94.29	73.46
		8.6	96.04	76.03
		10.6	97.37	80.58
		12.6	98.28	83.34
		14.6	97.73	87.15
		16.6	98.22	89.63
		18.6	98.73	91.43
		20.8	94.40	91.22
7	3.00	4.0	66.98	63.84
		4.6	93.46	68.02
		6.6	89.61	71.05
		8.6	91.45	76.29
		10.6	92.67	80.60
		12.6	94.23	84.92
		14.6	95.02	89.31
		16.6	96.43	92.24
		18.6	97.05	94.67
		21.6	84.23	97.34
8	4.00	2.6	95.28	62.19
		4.6	95.33	70.84
		6.6	7.60	69.18
		8.6	96.74	78.28
		10.6	97.37	83.30
		12.6	97.44	87.38
		14.6	97.40	90.92
		17.6	97.43	95.50
		20.6	97.82	96.09
		23.1	69.31	91.19
9	5.00	3.1	85.72	58.30
		4.6	95.46	62.84
		6.6	96.38	67.22
		8.6	96.97	70.91
		10.6	97.12	74.92
		12.6	97.71	76.69
		14.6	98.17	80.78
		16.6	98.05	82.38
		18.6	97.33	83.20
		20.6	94.41	83.17
		22.6	95.80	76.94
11	6.50	2.6	53.81	61.18
		4.6	91.65	69.95
		6.6	92.90	75.95
		8.6	92.98	81.30
		10.6	93.82	84.48
		12.6	93.59	87.52
		14.6	93.64	90.19
		17.6	95.36	92.72
		20.6	93.78	90.55
		23.1	69.58	86.38
14	7.50	2.6	96.05	66.69
		4.6	96.60	73.94
		6.6	96.73	80.45
		8.6	96.17	84.21
		23.4	80.51	85.51
		10.6	96.49	86.83
		20.6	90.23	89.10
		12.6	96.62	89.92
		17.6	93.11	92.05

Table E.7 Culvert Placed at an Embedment of 0.2*D* with a Discharge of 50 L/s.

Hole	x (m)	z (m)	% good samples	u (cm/s)
1	0.25	2.6	61.36	70.54
		4.6	94.78	62.71
		6.6	96.63	66.30
		8.6	96.95	69.25
		10.6	97.39	69.84
		12.6	97.69	70.82
		14.6	97.91	70.47
		16.6	98.49	69.60
2	0.50	4.6	93.95	66.49
		8.6	94.33	71.01
		10.6	94.84	71.40
		12.6	96.34	71.53
		14.6	97.06	71.18
		16.6	96.77	69.81
		18.6	95.18	69.03
4	1.00	2.6	93.53	58.13
		4.6	79.00	63.57
		7.6	70.10	67.39
		9.1	96.53	68.62
		11.1	96.53	69.04
		13.1	94.78	69.37
		15.1	90.93	69.35
		17.1	88.21	67.83
5	1.50	2.6	93.66	54.66
		4.6	81.38	62.68
		6.6	2.03	64.21
		8.6	93.53	68.80
		10.6	95.27	68.71
		12.6	95.61	66.12
		14.6	97.58	61.58
		16.6	97.41	61.21
		18.6	98.00	55.93
6	2.00	2.6	78.38	49.53
		5.1	68.43	58.22
		8.1	88.76	63.53
		9.6	95.58	65.63
		11.6	97.47	65.12
		13.6	98.26	63.03
		15.6	98.93	59.36
		17.6	99.03	56.48

Hole	z (m)	x (m)	% good samples	u (cm/s)
8	4.00	2.6	91.22	42.98
		4.6	73.57	47.98
		8.6	97.58	56.27
		10.6	97.97	57.50
		12.6	98.79	57.38
		14.6	98.62	56.88
		17.1	99.44	55.23
		19.6	99.21	53.67
9	5.00	3.6	98.91	43.05
		5.6	7.87	47.79
		7.6	20.23	50.08
		9.6	97.67	53.01
		11.6	97.69	54.98
		13.6	97.73	55.36
		15.6	98.69	55.54
		18.6	99.05	54.29
		21.6	96.84	51.56
11	6.50	2.6	92.49	39.54
		4.6	96.22	43.75
		8.6	97.50	51.97
		10.6	96.71	54.06
		12.6	97.28	55.71
		14.6	97.89	55.72
		18.1	98.72	54.47
		21.6	99.03	51.47
14	7.50	2.6	98.76	42.56
		4.6	4.18	46.00
		6.6	2.83	50.17
		8.6	96.86	53.80
		10.6	96.42	55.56
		12.6	97.54	56.24
		14.6	98.11	56.02

Table E.8 Culvert Placed at an Embedment of 0.2*D* with a Discharge of 70 L/s.

Hole	x (m)	z (m)	% good samples	u (cm/s)
1	0.25	1.9	94.57	56.21
		2.6	91.87	58.88
		5.6	89.84	65.99
		7.6	91.28	68.19
		9.6	92.64	69.27
		11.6	94.05	69.79
		13.6	95.23	70.22
		15.6	94.74	72.27
		17.6	96.59	71.97
		19.6	97.66	71.18
2	0.50	4.6	85.67	66.15
		6.6	87.12	69.39
		8.6	88.22	73.45
		10.6	90.94	74.90
		12.6	76.73	75.04
		14.6	76.40	75.99
		17.1	93.12	75.63
		19.6	95.64	74.88
		21.6	93.69	74.23
4	1.00	1.6	41.66	52.25
		2.6	65.20	55.47
		5.6	69.28	64.23
		7.6	76.42	66.11
		9.6	78.26	67.23
		11.6	57.15	70.70
		13.6	61.63	70.95
		15.6	68.65	70.83
		17.6	76.18	69.94
		19.6	74.65	69.84
5	1.50	2.6	82.70	57.99
		4.6	90.74	65.16
		6.6	91.64	70.31
		8.6	91.75	72.75
		10.6	92.97	73.60
		12.6	91.73	77.16
		14.6	91.40	77.28
		17.1	88.74	77.38
		19.6	88.66	76.23
		21.6	86.97	76.00
6	2.00	6.1	75.21	66.97
		7.6	95.54	69.13
		9.6	94.88	71.83
		11.6	94.13	73.95
		13.6	95.14	74.95
		15.6	95.00	75.36
		17.6	95.41	75.31
		19.6	93.15	74.79
		21.6	87.77	72.09
		23.6	93.91	66.89
7	3.00	3.1	75.29	47.70
		4.1	84.75	52.99
		6.1	82.89	59.42
		8.1	84.78	63.72
		10.1	86.78	68.77
		12.1	89.33	71.26
		14.1	90.79	72.03
		16.1	92.87	70.64
		18.1	95.11	70.76
		20.1	95.81	67.74
		22.1	98.35	63.38
		24.1	99.40	61.95
8	4.00	2.6	81.49	48.50
		4.6	84.23	56.40
		6.6	86.32	59.42
		8.6	88.78	63.80
		10.6	88.99	66.94
		12.6	87.20	71.14
		14.6	87.66	71.67
		17.6	77.39	69.14
		21.1	70.41	67.02
		23.6	85.40	63.42
9	5.00	2.6	80.73	45.05
		4.6	80.69	50.87
		6.6	82.08	55.14
		8.6	82.95	59.88
		10.6	84.70	63.28
		12.6	87.18	64.30
		14.6	89.11	66.23
		16.6	91.40	65.98
		18.6	83.25	63.33
		20.6	97.64	43.55
		22.6	98.43	56.52
		24.6	90.06	60.15
11	6.50	2.6	36.25	46.15
		4.6	92.02	53.03
		6.6	92.25	56.82
		8.6	83.92	60.66
		10.6	85.96	63.38
		12.6	84.26	65.59
		14.6	84.38	68.16
		17.6	93.34	64.06
		21.1	89.38	67.02
		24.1	94.30	62.91
14	7.50	4.6	81.16	51.93
		6.6	80.37	56.83
		8.6	84.23	59.63
		10.6	86.89	61.78
		12.6	85.81	64.71
		14.6	89.19	65.81
		18.1	94.53	64.65
		21.6	71.55	47.01
		24.6	84.31	57.61

Table E.9 Culvert Placed at an Embedment of 0.2*D* with a Discharge of 90 L/s.

Hole	x (m)	z (m)	% good samples	u (cm/s)
1	0.25	2.1	96.94	66.83
		2.6	97.95	67.59
		4.6	98.81	70.71
		6.6	98.92	72.50
		8.6	98.52	75.06
		10.6	97.94	77.81
		12.6	98.19	80.38
		14.6	98.30	82.25
		16.6	98.95	83.21
		18.6	98.74	83.53
		20.6	98.69	83.71
		22.6	96.84	77.64
2	0.50	4.6	96.70	75.75
		6.6	96.29	77.90
		8.6	95.67	80.13
		10.6	95.01	82.28
		12.6	94.14	84.62
		14.6	93.77	86.37
		17.1	92.03	85.35
		19.6	92.48	86.03
		21.6	92.63	85.69
		23.6	91.90	85.11
4	1.00	1.5	87.37	51.43
		2.6	83.74	55.78
		4.6	88.09	61.91
		6.6	92.84	66.10
		8.6	97.13	68.99
		10.6	96.03	70.35
		12.6	86.80	73.09
		14.6	87.71	75.84
		16.6	87.69	77.35
		18.6	86.74	79.06
		20.6	90.75	75.79
		22.6	94.36	81.33
5	1.50	2.6	26.09	51.31
		4.6	95.11	58.80
		6.6	95.05	63.70
		8.6	94.92	67.46
		10.6	95.23	71.86
		12.6	95.25	75.16
		14.6	94.70	77.93
		17.1	96.20	80.25
		19.6	95.46	82.66
		21.6	95.59	83.12
		24.6	96.42	82.66
6	2.00	1.8	73.99	45.49
		2.6	92.77	48.21
		4.6	73.22	50.22
		6.6	76.43	56.48
		8.6	77.89	59.56
		11.6	80.98	64.88
		14.6	86.26	69.71
		17.6	88.54	74.25
		20.6	91.29	76.95
		23.6	94.28	78.80
		26.6	73.14	78.49
7	3.00	2.6	68.56	47.99
		3.6	83.88	50.13
		5.6	83.29	53.74
		7.6	85.09	56.72
		9.6	89.22	59.37
		12.6	90.69	64.37
		15.6	91.37	68.99
		18.6	94.55	72.65
		21.6	96.95	77.12
		24.6	98.44	77.84
		27.6	98.45	75.47
8	4.00	2.6	93.74	51.19
		4.6	93.76	54.87
		6.6	94.96	60.16
		8.6	95.66	63.00
		10.6	96.70	66.29
		12.6	93.44	68.77
		14.6	93.06	71.81
		17.1	92.18	75.39
		20.1	94.67	79.14
		22.6	95.29	80.27
		25.6	95.06	78.67
9	5.00	2.6	82.65	49.37
		3.6	70.79	53.52
		5.6	70.84	57.81
		7.6	74.23	60.25
		9.6	77.47	63.90
		12.6	77.16	67.85
		15.6	74.35	71.49
		18.6	70.49	74.74
		21.6	82.18	76.09
		24.6	86.12	76.37
		27.6	86.50	74.15
11	6.50	2.6	87.69	51.25
		4.6	93.35	57.51
		6.6	96.01	60.45
		8.6	97.25	64.43
		10.6	98.39	67.07
		12.6	96.85	70.34
		14.6	97.06	72.72
		17.1	95.01	73.42
		21.1	95.94	75.07
		24.1	96.46	74.53
		27.1	97.25	71.92
14	7.50	2.6	78.38	55.17
		4.6	82.56	59.50
		6.6	86.02	64.67
		8.6	89.61	66.10
		10.6	89.88	69.56
		12.6	89.88	71.62
		14.6	91.27	73.57
		17.1	83.12	75.34
		21.1	85.98	75.01
		24.1	88.46	73.78
		27.1	91.32	70.57

APPENDIX F

Up-looking ADV Probe to Verify Velocities near the Water Surface

F.1 Introduction

The down-looking ADV probe used in this study could not be used to measure velocities within 5 cm of the water surface; however, an up-looking probe can measure velocities near the water surface. An up-looking ADV probe became available near the end of the research program; therefore, the up-looking probe was used in an effort to: (1) check whether the use of a down looking probe only was adequate, and (2) assess the consequent impact on the results of using the down-looking probe only and/or how the down-looking results could be adjusted accordingly. In other words, the up-looking probe was used to determine the quality of the results with the down-looking probe only and/or the added value of the additional results provided by the up-looking probe.

Contour results from two tests are used in the comparison. Both test were conducted at Hole 8 (i.e. 4 m from the culvert inlet) with the culvert embedded 0.1 times the culvert diameter. The first test was at a discharge of 50 L/s and the second test was at 90 L/s. Figure F.1 shows the locations within the cross-section that measurements were taken with the up-looking ADV probe.

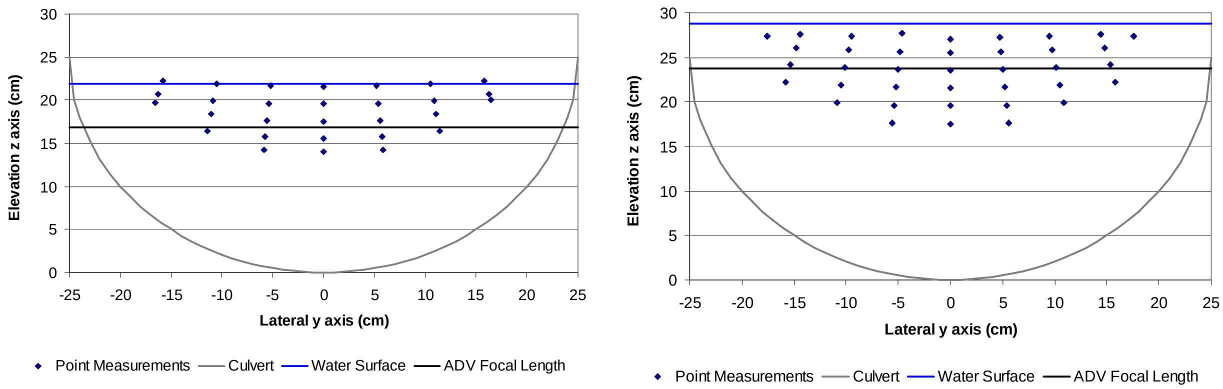

Figure F.1 Measurement locations when using the up-looking ADV at Hole 8 when the culvert was embedded 0.1*D* for discharges of a) 50 L/s and b) 90 L/s.

F.2 Contour Plots: A Visual Comparison

Figures F.2 and F.3 compare the streamwise velocity results from (1) only the down-looking probe to (2) the results of using both the down-looking and up-looking probes. These plots were created using the radial plotting method in Surfer. On the bases of a visual comparison, the results appear very similar.

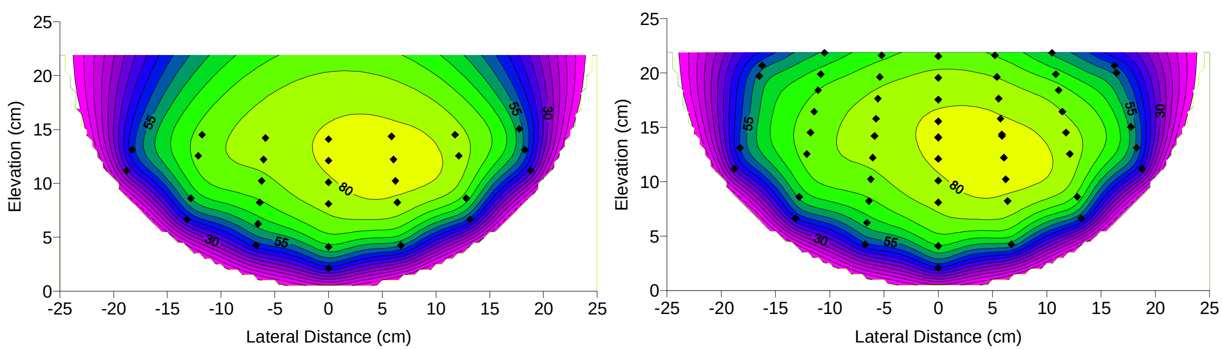

Figure F.2 Streamwise velocity at Hole 8 using only the down-looking ADV and using both the up-looking and down-looking ADVs for a discharge of 50 L/s and an embedment of 0.1*D*.

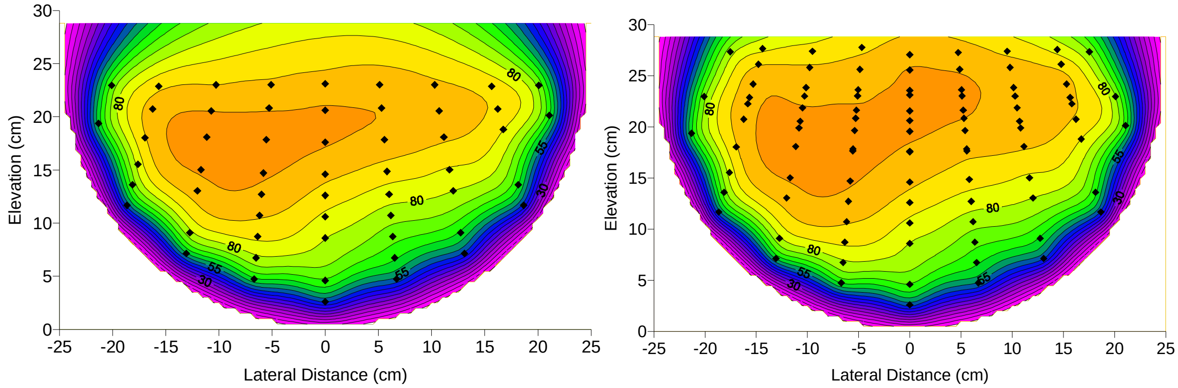

Figure F.3 Streamwise velocity at Hole 8 using only the down-looking ADV and using both the up-looking and down-looking ADVs for a discharge of 90 L/s and an embedment of 0.1*D*.

F.3 Velocity-Area Integration Comparison

A velocity-area integration of the contour plots was conducted to determine a discharge and mean velocity value, respectively. The integrated discharge value was calculated by summing the velocity of each contour multiplied by the cross-sectional area. This calculated discharge value was divided by the cross-sectional area to get the integrated velocity value. Tables F.1 and F.2 compare the measured discharge and calculated average velocity results using only the down-looking probe and the results using both the down-looking and up-looking probes. Also, the results of the integration using the radial plotting methods are shown. The measured average velocity was calculated by dividing the measured discharge by the computed (based on flow depth and culvert geometry) cross-sectional area.

Table F.1 Comparison for tests using a discharge of 50 L/s.

	Q (L/s)	V (cm/s)	Q % Diff	V % Diff
Measured	50.1	60.5	0.0	0.0
Down-looking only	46.7	58.1	-7.0	-4.0
Both down-looking and up-looking	47.3	58.8	-5.7	-2.8

Table F.2 Comparison for tests using a discharge of 90 L/s.

	Q (L/s)	V (cm/s)	Q % Diff	V % Diff
Measured	89.8	76.8	0.0	0.0
Down-looking only	82.6	72.3	-8.4	-6.0
Both down-looking and up-looking	84.7	74.1	-5.8	-3.6

F.4 Conclusion

At 50 L/s, the discharge found by integration improved by only 1.3%, while the average velocity improved by only 1.2%. At 90 L/s, the discharge found by velocity-area integration improved by only 2.6%, while the average velocity improved by only 2.4%.

When comparing individual point measurements where the down-looking and up-looking probe measurements overlapped, there was approximately 1 cm/s difference for the points at 50 L/s and approximately 5 cm/s for points at 90 L/s.

Less low percent difference suggest that the use of the down-looking probe was adequate and not worth the time to be supplemented with the up-looking probe.

APPENDIX G

Streamwise Velocity and Turbulence Intensity Distribution Plots

The streamwise velocity, turbulence intensity and non-dimensionalized streamwise velocity distributions are presented in Figures F.2 to F10. For ease of comparison, each figure is presented in such a way that the progression along the length of the culvert and the change among culvert placements can be seen all at once. In other words, each figure has 15 contour plots arranged such that the location of the contour plot is shown from top to bottom and the placement of the culvert is shown from left to right. Figure F.1 clarifies the way in which the contour plots are presented.

Progression of embedment →

Progression along length of culvert ↓

At Grade	Embedment of 0.1*D*	Embedment of 0.2*D*
x = 0.5m	x = 0.5m	x = 0.5m
x = 1.5m	x = 1.5m	x = 1.5m
x = 4.0 m	x = 4.0 m	x = 4.0 m
x = 6.5 m	x = 6.5 m	x = 6.5 m
x = 7.5 m	x = 7.5 m	x = 7.5 m

Figure G.1 Arrangement of contour plots presented in Figures G.2 to G.10.

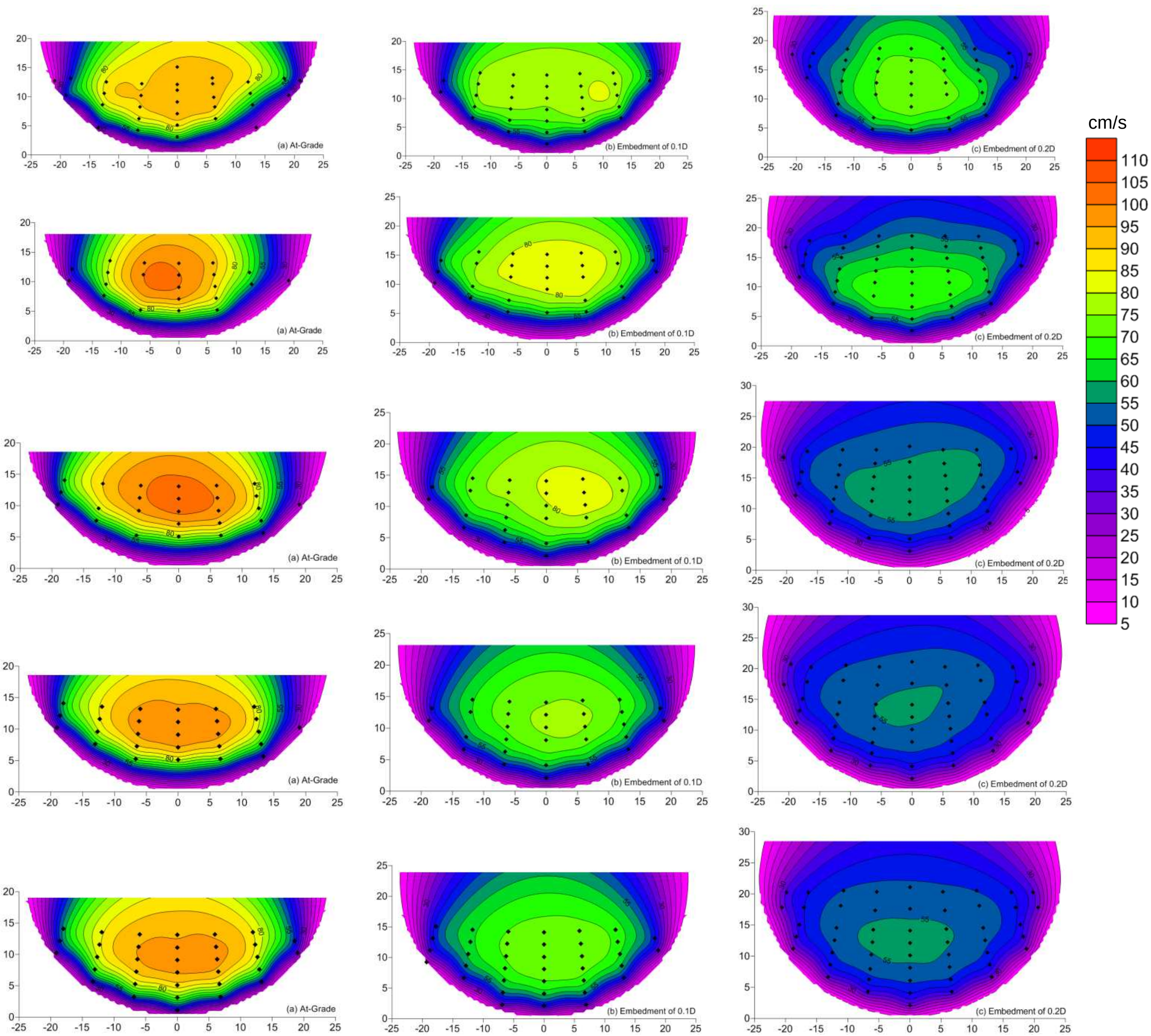

Figure G.2 Streamwise velocity distributions in cm/s for a discharge of 50 L/s

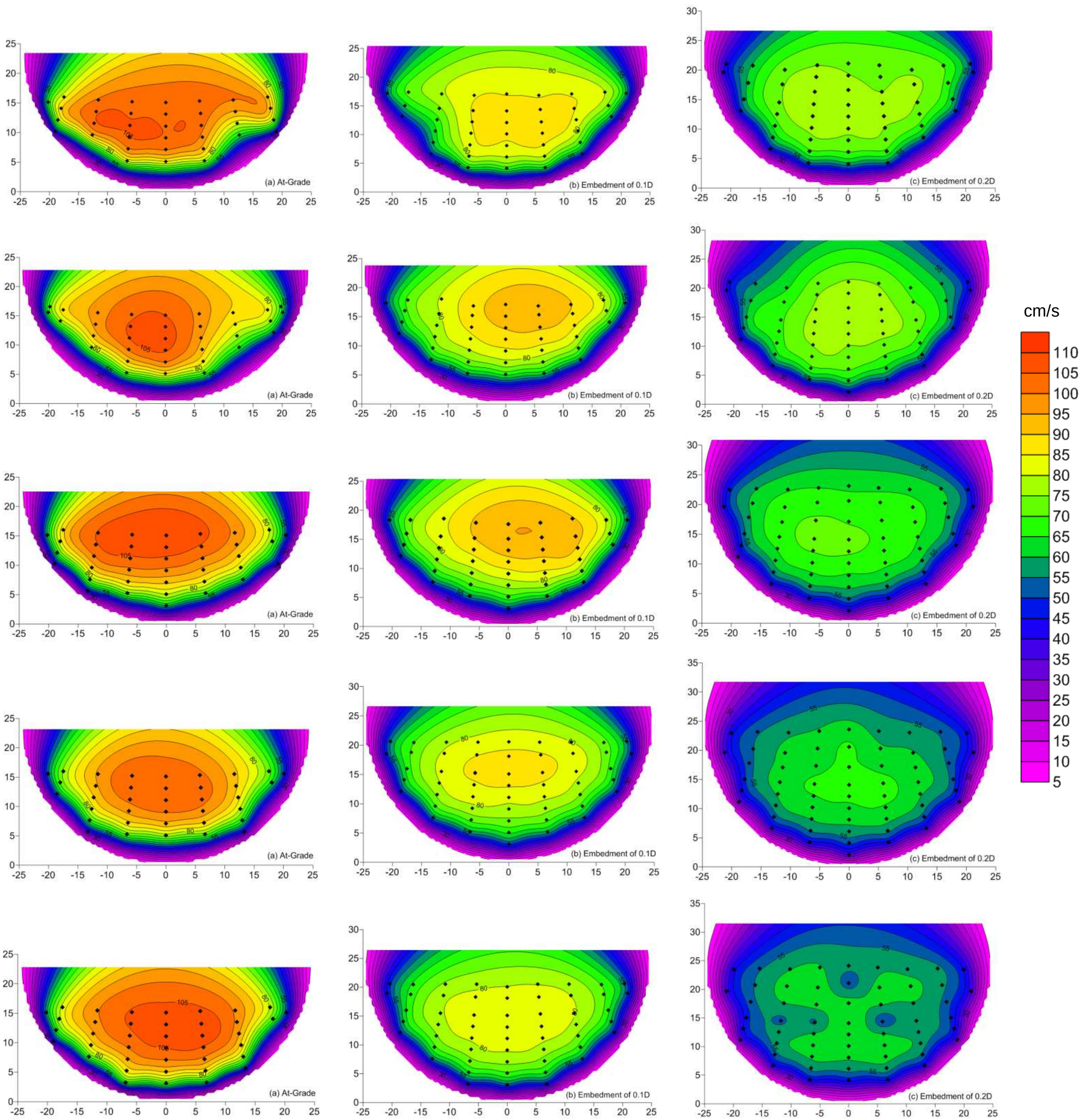

Figure G.3 Streamwise velocity distributions in cm/s for a discharge of 70 L/s.

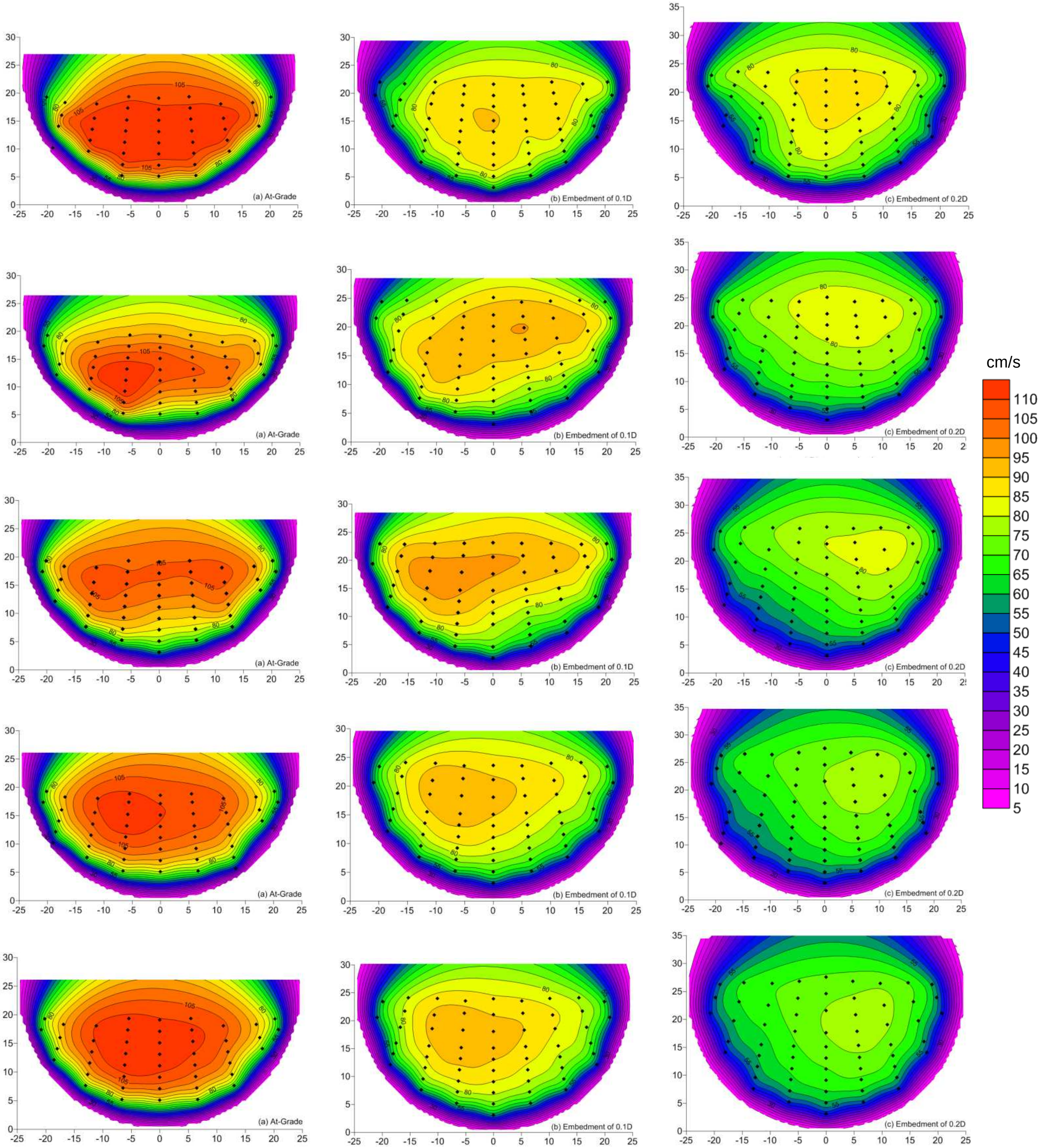

Figure G.4 Streamwise velocity distributions in cm/s for a discharge of 90 L/s.

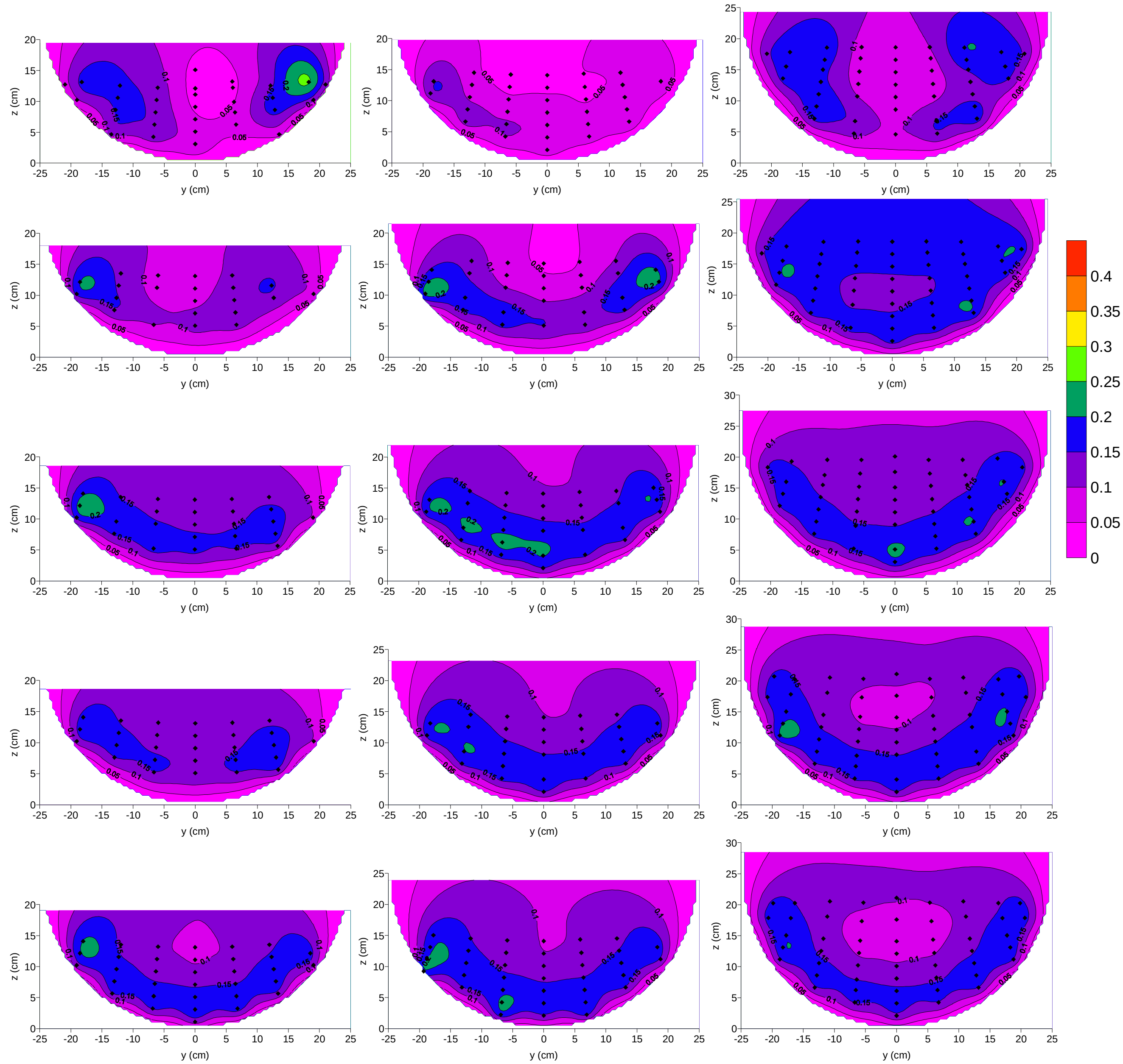

Figure G.5. Streamwise turbulence intensity distributions for a discharge of 50 L/s.

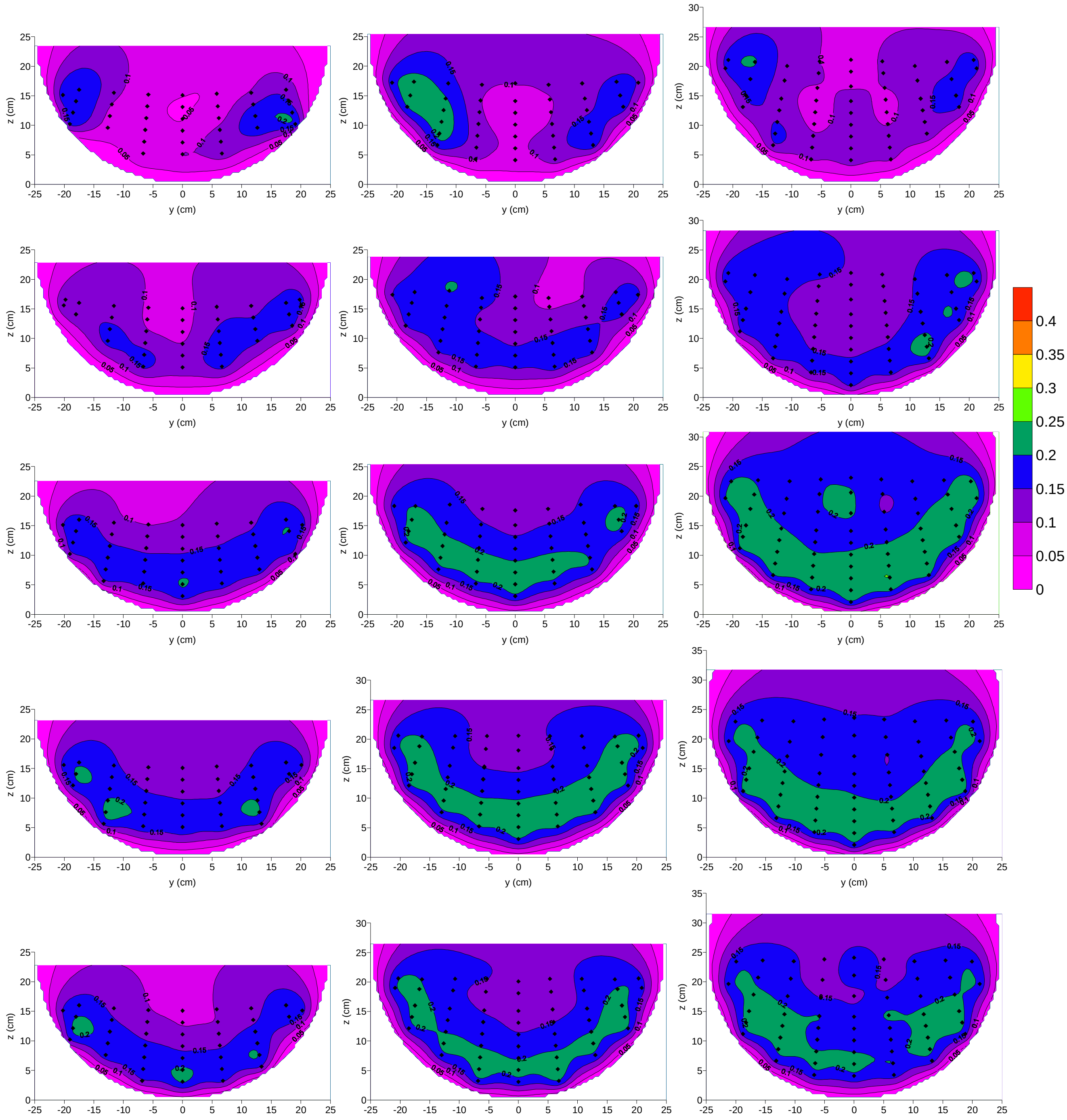

Figure G.6. Streamwise turbulence intensity distributions for a discharge of 70 L/s.

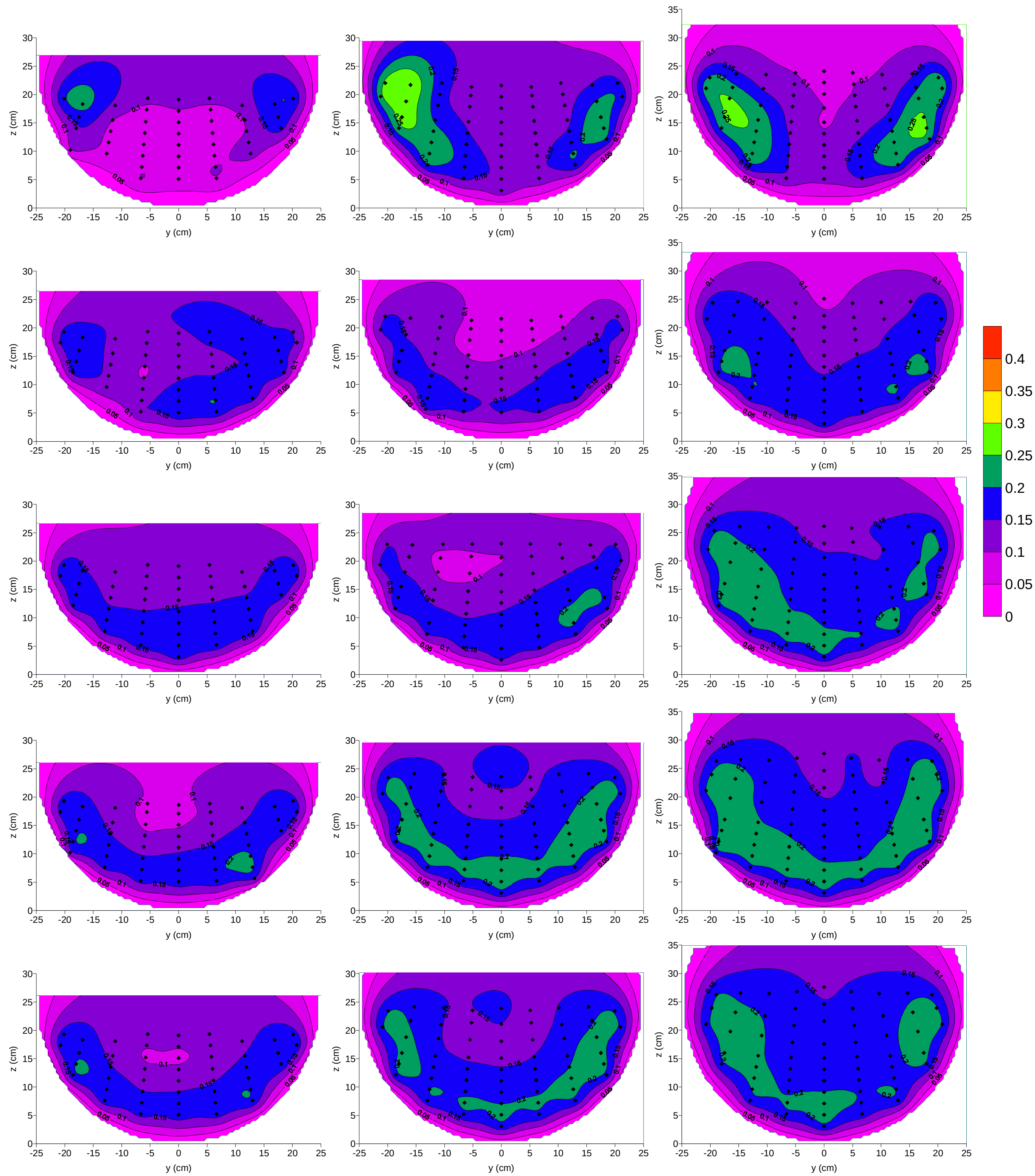

Figure G.7. Streamwise turbulence intensity distributions for a discharge of 90 L/s.

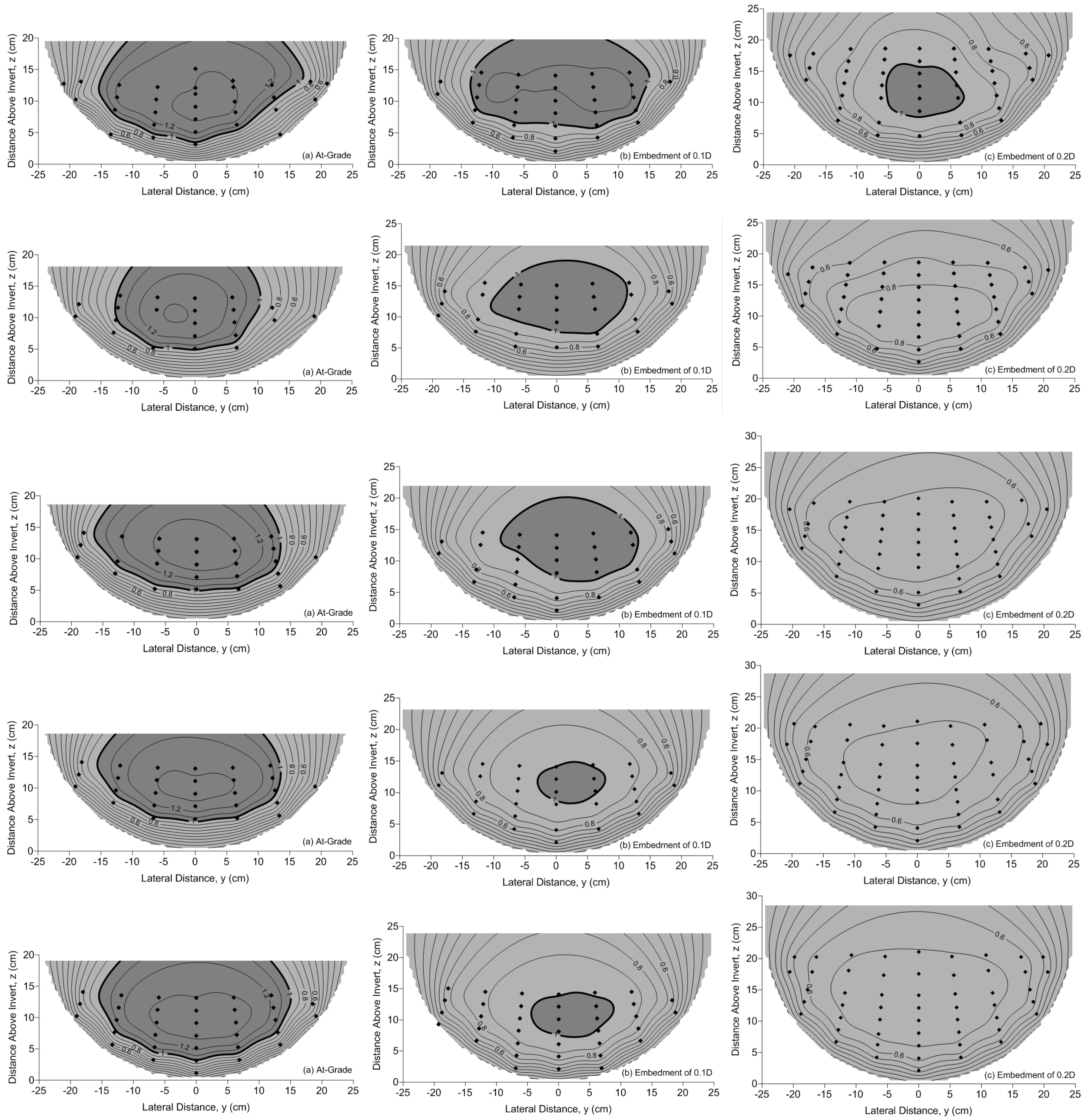

Figure G.8 Nondimensional streamwise velocity distributions for a discharge of 50 L/s.

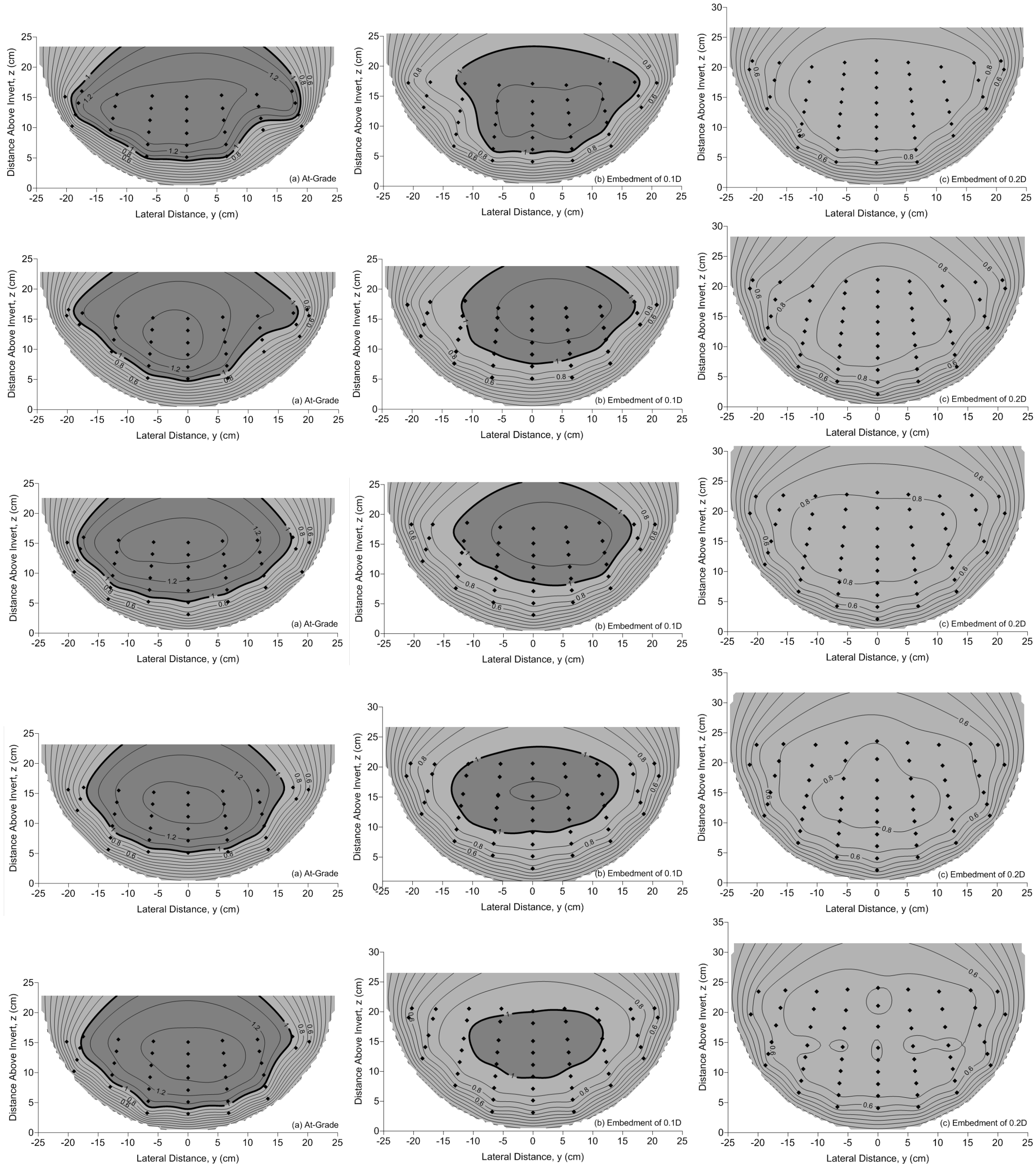

Figure G.9 Nondimensional streamwise velocity distributions for a discharge of 70 L/s.

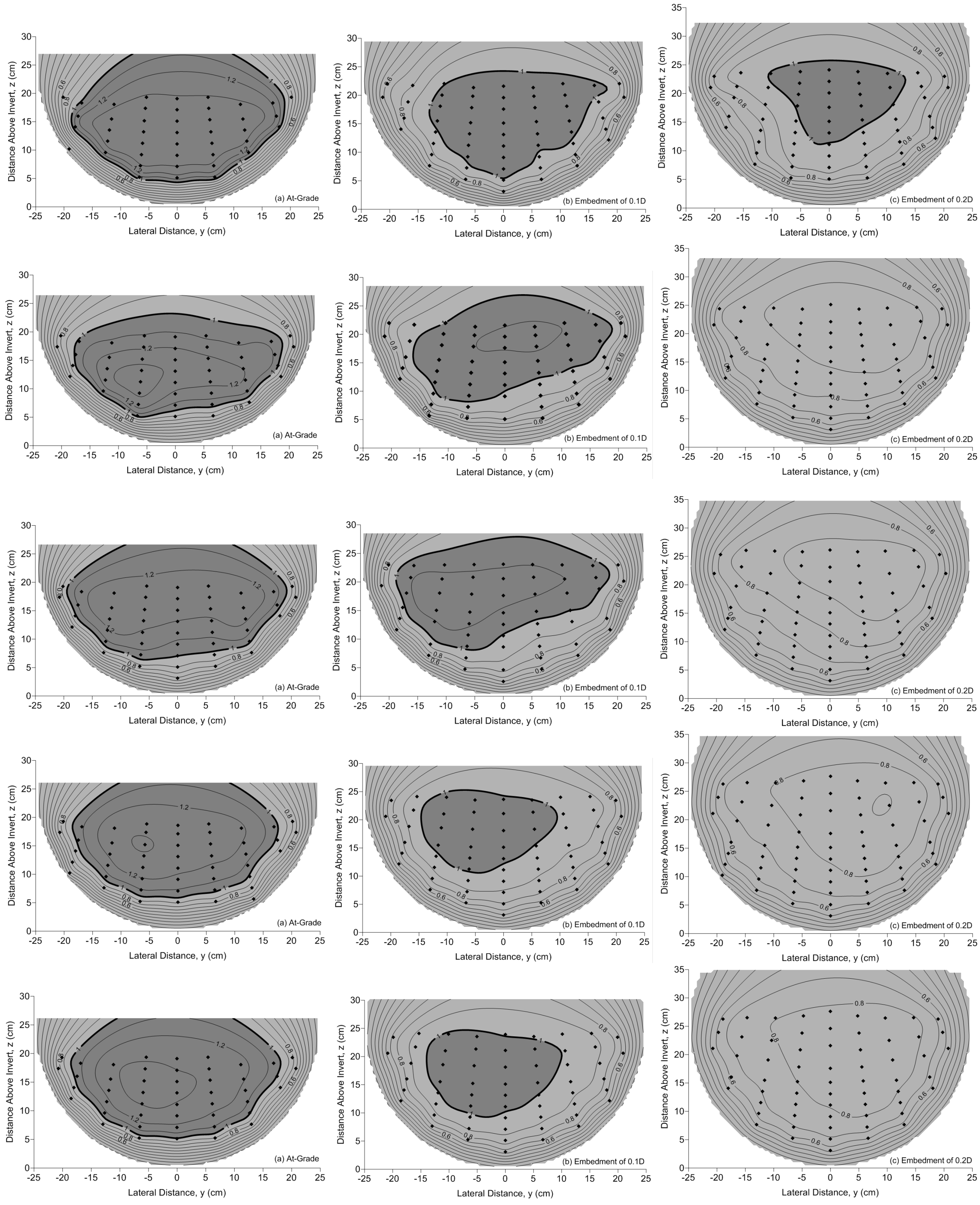

Figure G.10 Nondimensional streamwise velocity distributions for a discharge of 90 L/s.

APPENDIX H

Streamwise Velocity Comparison to Ead et al. (2000)

Being able to predict the velocity distribution within the culvert can be helpful for culvert designs. For example, if a target fish species and size are known, then one can calculate the velocity distribution within the culvert to ensure that there is physically enough space within the culvert where velocities are low enough to accommodate the fish's swimming ability.

Ead et al. (2000) expanded the Prandtl-von Karman equations for one-dimensional vertical velocity distribution for the rough flow regime to account for non-central velocity preditions. Velocity measurements taken during this research study when the culvert was placed at grade were compared to the results found using the Ead et al. (2000) equations (i.e., Equations 2.3 to 2.8 of the main body of this document).

Characteristics measured during this research study, such as discharge, culvert slope, culvert diameter, specific point measurement locations (i.e., the z and y coordinate identifying its location within the culvert cross-section), were inserted into Equations 2.3 to 2.8. The shear velocities at the central axis required in Equation 2.8 were calculated and are shown in Table 5.2. The Ead et al. (2000) equations provided a streamwise velocity at the specified coordinates. The measured streamwise velocity was compared to the calculated streamwise velocity.

Table H.1 Culvert Placed at Grade with a Discharge of 50 L/s x = 0.5 (Hole 2)

Lateral Distance (m)	Distance Above Invert (m)	Streamwise velocity measured (m/s)	Streamwise velocity predicted by Ead et al. 2000 (m/s)	Percent Error
0.000	0.151	0.919	1.04	-12%
0.000	0.121	0.912	1.03	-12%
0.000	0.111	0.916	1.02	-10%
0.000	0.091	0.920	0.99	-7%
0.000	0.071	0.913	0.94	-3%
0.000	0.051	0.899	0.88	2%
0.000	0.031	0.808	0.79	3%
0.060	0.132	0.910	0.99	-8%
0.060	0.122	0.914	1.00	-8%
0.062	0.099	0.924	1.00	-8%
0.064	0.082	0.909	0.97	-6%
0.066	0.062	0.907	0.92	-1%
0.121	0.126	0.867	0.88	-1%
0.125	0.106	0.740	0.91	-19%
0.128	0.086	0.592	0.94	-37%
0.135	0.047	0.293	0.86	-66%
0.183	0.131	0.739	0.49	50%
0.190	0.102	0.383	0.55	-30%
0.210	0.127	0.474	0.09	450%
			Average	15%
			Maximum	450%
			Minimum	-66%
			Std. Dev.	108%

	-------- Percent Error --------		
Lateral Distance (m)	Average	Maximum	Minimum
0	-6%	3%	-12%
0.00 to 0.10	-6%	-1%	-8%
0.10 to 0.15	-31%	-1%	-66%
0.15 to 0.25	156%	450%	-30%

Table H.2 Culvert Placed at Grade with a Discharge of 50 L/s x = 1.5 (Hole 5)

Lateral Distance (m)	Distance Above Invert (m)	Streamwise velocity measured (m/s)	Streamwise velocity predicted by Ead et al. 2000 (m/s)	Percent Error
0.000	0.131	0.978	1.04	-6%
0.000	0.111	0.996	1.02	-3%
0.000	0.091	0.987	0.99	0%
0.000	0.071	0.970	0.94	3%
0.000	0.051	0.884	0.88	1%
0.060	0.132	0.930	0.99	-6%
0.061	0.112	0.900	1.01	-11%
0.063	0.092	0.838	0.99	-15%
0.065	0.072	0.859	0.94	-9%
0.067	0.052	0.816	0.88	-8%
0.123	0.116	0.708	0.89	-21%
0.126	0.096	0.608	0.93	-34%
0.190	0.102	0.365	0.55	-33%
			Average	-11%
			Maximum	3%
			Minimum	-34%
			Std. Dev.	12%

	-------- Percent Error --------		
Lateral Distance (m)	Average	Maximum	Minimum
0	-1%	3%	-6%
0.00 to 0.10	-10%	-6%	-15%
0.10 to 0.15	-28%	-21%	-34%
0.15 to 0.25	-33%	-33%	-33%

Table H.3 Culvert Placed at Grade with a Discharge of 50 L/s x = 4.0 (Hole 8)

Lateral Distance (m)	Distance Above Invert (m)	Streamwise velocity measured (m/s)	Streamwise velocity predicted by Ead et al. 2000 (m/s)	Percent Error
0.000	0.131	1.00	1.05	-4%
0.000	0.111	1.04	1.03	1%
0.000	0.091	1.03	1.00	3%
0.000	0.071	0.91	0.95	-4%
0.000	0.051	0.86	0.89	-3%
0.060	0.132	0.96	1.00	-4%
0.061	0.112	1.00	1.02	-2%
0.063	0.092	0.96	1.00	-4%
0.065	0.072	0.93	0.95	-2%
0.067	0.052	0.84	0.89	-6%
0.119	0.135	0.84	0.86	-2%
0.123	0.116	0.82	0.90	-9%
0.126	0.096	0.81	0.94	-13%
0.130	0.076	0.72	0.96	-25%
0.133	0.057	0.54	0.91	-40%
0.190	0.102	0.37	0.55	-33%
			Average	-9%
			Maximum	3%
			Minimum	-40%
			Std. Dev.	12%

	-------- Percent Error --------		
Lateral Distance (m)	Average	Maximum	Minimum
0	-1%	3%	-4%
0.00 to 0.10	-4%	-2%	-6%
0.10 to 0.15	-18%	-2%	-40%
0.15 to 0.25	-33%	-33%	-33%

Table H.4 Culvert Placed at Grade with a Discharge of 50 L/s x = 6.5 (Hole 11)

Lateral Distance (m)	Distance Above Invert (m)	Streamwise velocity measured (m/s)	Streamwise velocity predicted by Ead et al. 2000 (m/s)	Percent Error
0.000	0.131	0.940	1.04	-10%
0.000	0.111	0.973	1.02	-5%
0.000	0.091	0.986	0.99	0%
0.000	0.071	0.953	0.94	1%
0.000	0.051	0.885	0.88	1%
0.060	0.132	0.934	0.99	-6%
0.061	0.112	0.972	1.01	-3%
0.063	0.092	0.955	0.99	-3%
0.065	0.072	0.911	0.94	-3%
0.067	0.052	0.821	0.88	-7%
0.119	0.135	0.851	0.86	-1%
0.123	0.116	0.837	0.89	-6%
0.126	0.096	0.798	0.93	-14%
0.130	0.076	0.701	0.95	-26%
0.133	0.057	0.543	0.90	-40%
0.190	0.102	0.371	0.55	-32%
			Average	-10%
			Maximum	1%
			Minimum	-40%
			Std. Dev.	12%

	-------- Percent Error --------		
Lateral Distance (m)	Average	Maximum	Minimum
0	-2%	1%	-10%
0.00 to 0.10	-5%	-3%	-7%
0.10 to 0.15	-17%	-1%	-40%
0.15 to 0.25	-32%	-32%	-32%

Table H.5 Culvert Placed at Grade with a Discharge of 50 L/s x = 7.5 (Hole 14)

Lateral Distance (m)	Distance Above Invert (m)	Streamwise velocity measured (m/s)	Streamwise velocity predicted by Ead et al. 2000 (m/s)	Percent Error
0.000	0.131	0.927	1.04	-11%
0.000	0.111	0.964	1.02	-6%
0.000	0.091	0.971	0.99	-2%
0.000	0.071	0.947	0.94	1%
0.000	0.051	0.886	0.88	1%
0.000	0.031	0.766	0.79	-3%
0.000	0.011	0.630	0.60	6%
0.060	0.132	0.934	0.99	-6%
0.061	0.112	0.957	1.01	-5%
0.063	0.092	0.956	0.99	-3%
0.065	0.072	0.935	0.94	-1%
0.067	0.052	0.855	0.88	-3%
0.068	0.032	0.716	0.80	-10%
0.119	0.135	0.855	0.86	0%
0.123	0.116	0.845	0.89	-5%
0.126	0.096	0.812	0.93	-12%
0.130	0.076	0.750	0.95	-21%
0.133	0.057	0.629	0.90	-30%
0.185	0.121	0.562	0.51	10%
0.190	0.102	0.488	0.55	-11%
			Average	-6%
			Maximum	10%
			Minimum	-30%
			Std. Dev.	9%

	-------- Percent Error --------		
Lateral Distance (m)	Average	Maximum	Minimum
0	-2%	6%	-30%
0.00 to 0.10	-5%	-1%	-10%
0.10 to 0.15	-14%	0%	-30%
0.15 to 0.25	-1%	10%	-11%

Table H.6 Culvert Placed at Grade with a Discharge of 70 L/s x = 0.5 (Hole 2)

Lateral Distance (m)	Distance Above Invert (m)	Streamwise velocity measured (m/s)	Streamwise velocity predicted by Ead et al. 2000 (m/s)	Percent Error
0.00	0.15	1.02	1.06	-3%
0.00	0.13	1.03	1.04	-1%
0.00	0.11	1.03	1.02	1%
0.00	0.09	1.03	0.98	5%
0.00	0.07	1.02	0.94	8%
0.00	0.05	0.92	0.88	5%
0.06	0.15	1.02	1.01	1%
0.06	0.13	1.03	1.01	2%
0.06	0.11	1.02	1.01	1%
0.06	0.09	0.98	0.99	-1%
0.06	0.07	0.93	0.94	-1%
0.07	0.05	0.92	0.88	4%
0.12	0.16	1.00	0.92	10%
0.12	0.14	0.95	0.93	2%
0.12	0.12	0.79	0.94	-16%
0.13	0.10	0.63	0.96	-34%
0.17	0.16	0.95	0.69	39%
0.18	0.14	0.97	0.70	37%
0.19	0.12	0.94	0.72	31%
0.19	0.10	0.62	0.73	-16%
			Average	4%
			Maximum	39%
			Minimum	-34%
			Std. Dev.	17%

	-------- Percent Error --------		
Lateral Distance (m)	Average	Maximum	Minimum
0	2%	8%	-3%
0.00 to 0.10	1%	4%	-1%
0.10 to 0.15	-10%	10%	-34%
0.15 to 0.25	23%	39%	-16%

Table H.7 Culvert Placed at Grade with a Discharge of 70 L/s x = 1.5 (Hole 5)

Lateral Distance (m)	Distance Above Invert (m)	Streamwise velocity measured (m/s)	Streamwise velocity predicted by Ead et al. 2000 (m/s)	Percent Error
0.00	0.15	1.05	1.06	-1%
0.00	0.13	1.06	1.04	2%
0.00	0.11	1.06	1.02	4%
0.00	0.09	1.05	0.98	6%
0.00	0.07	1.01	0.94	7%
0.00	0.05	0.94	0.88	7%
0.06	0.15	0.98	1.01	-3%
0.06	0.13	0.97	1.01	-4%
0.06	0.11	0.95	1.01	-7%
0.06	0.09	0.91	0.99	-8%
0.06	0.07	0.87	0.94	-8%
0.07	0.05	0.81	0.88	-9%
0.12	0.16	0.88	0.92	-4%
0.12	0.14	0.83	0.93	-10%
0.12	0.12	0.76	0.94	-19%
0.13	0.10	0.69	0.96	-28%
0.17	0.16	0.84	0.69	22%
0.18	0.14	0.78	0.70	11%
0.19	0.12	0.67	0.72	-7%
0.20	0.17	0.75	0.49	54%
0.20	0.16	0.69	0.49	41%
			Average	2%
			Maximum	54%
			Minimum	-28%
			Std. Dev.	19%

	-------- Percent Error --------		
Lateral Distance (m)	Average	Maximum	Minimum
0	4%	7%	-1%
0.00 to 0.10	-6%	-3%	-9%
0.10 to 0.15	-15%	-4%	-28%
0.15 to 0.25	24%	54%	-7%

Table H.8 Culvert Placed at Grade with a Discharge of 70 L/s x = 4.0 (Hole 8)

Lateral Distance (m)	Distance Above Invert (m)	Streamwise velocity measured (m/s)	Streamwise velocity predicted by Ead et al. 2000 (m/s)	Percent Error
0.00	0.15	1.08	1.06	3%
0.00	0.13	1.08	1.04	4%
0.00	0.11	1.04	1.02	1%
0.00	0.09	0.98	0.98	0%
0.00	0.07	0.90	0.94	-5%
0.00	0.05	0.81	0.88	-8%
0.00	0.03	0.72	0.79	-9%
0.06	0.15	1.07	1.01	6%
0.06	0.13	1.05	1.01	3%
0.06	0.11	0.99	1.01	-3%
0.06	0.09	0.92	0.99	-7%
0.06	0.07	0.85	0.94	-10%
0.07	0.05	0.77	0.88	-13%
0.12	0.16	0.99	0.92	8%
0.12	0.14	0.96	0.93	3%
0.12	0.12	0.88	0.94	-7%
0.13	0.10	0.82	0.96	-14%
0.13	0.08	0.73	0.95	-23%
0.17	0.16	0.83	0.69	20%
0.18	0.14	0.74	0.70	5%
0.19	0.10	0.62	0.73	-16%
0.20	0.15	0.65	0.49	33%
			Average	-1%
			Maximum	33%
			Minimum	-23%
			Std. Dev.	12%

	-------- Percent Error --------		
Lateral Distance (m)	Average	Maximum	Minimum
0	-2%	4%	-9%
0.00 to 0.10	-4%	6%	-13%
0.10 to 0.15	-7%	8%	-23%
0.15 to 0.25	11%	33%	-16%

Table H.9 Culvert Placed at Grade with a Discharge of 70 L/s x = 6.5 (Hole 11)

Lateral Distance (m)	Distance Above Invert (m)	Streamwise velocity measured (m/s)	Streamwise velocity predicted by Ead et al. 2000 (m/s)	Percent Error
0.00	0.15	1.02	1.06	-3%
0.00	0.13	1.05	1.04	0%
0.00	0.11	1.04	1.02	2%
0.00	0.09	0.99	0.98	1%
0.00	0.07	0.94	0.94	0%
0.00	0.05	0.84	0.88	-4%
0.06	0.15	1.01	1.01	0%
0.06	0.13	1.02	1.01	1%
0.06	0.11	1.01	1.01	0%
0.06	0.09	0.97	0.99	-2%
0.06	0.07	0.90	0.94	-4%
0.07	0.05	0.81	0.88	-9%
0.12	0.16	0.91	0.92	-1%
0.12	0.14	0.90	0.93	-3%
0.12	0.12	0.87	0.94	-8%
0.13	0.10	0.81	0.96	-16%
0.13	0.08	0.70	0.95	-27%
0.13	0.06	0.56	0.90	-38%
0.17	0.16	0.73	0.69	7%
0.18	0.14	0.69	0.70	-2%
0.20	0.16	0.58	0.49	20%
			Average	-4%
			Maximum	20%
			Minimum	-38%
			Std. Dev.	12%

	-------- Percent Error --------		
Lateral Distance (m)	Average	Maximum	Minimum
0	-1%	2%	-4%
0.00 to 0.10	-2%	1%	-9%
0.10 to 0.15	-15%	-1%	-38%
0.15 to 0.25	8%	20%	-2%

Table H.10 Culvert Placed at Grade with a Discharge of 70 L/s x = 7.5 (Hole 14)

Lateral Distance (m)	Distance Above Invert (m)	Streamwise velocity measured (m/s)	Streamwise velocity predicted by Ead et al. 2000 (m/s)	Percent Error
0.00	0.15	1.06	1.06	0%
0.00	0.13	1.07	1.04	3%
0.00	0.11	1.07	1.02	5%
0.00	0.09	1.05	0.98	6%
0.00	0.07	0.98	0.94	5%
0.00	0.05	0.91	0.88	3%
0.00	0.03	0.83	0.79	5%
0.06	0.15	1.05	1.01	4%
0.06	0.13	1.07	1.01	6%
0.06	0.11	1.07	1.01	5%
0.06	0.09	1.04	0.99	6%
0.06	0.07	0.97	0.94	3%
0.07	0.05	0.89	0.88	1%
0.07	0.03	0.77	0.80	-3%
0.12	0.16	0.99	0.92	8%
0.12	0.14	0.98	0.93	6%
0.12	0.12	0.95	0.94	1%
0.13	0.10	0.89	0.96	-6%
0.13	0.08	0.81	0.95	-15%
0.13	0.06	0.69	0.90	-24%
0.17	0.16	0.81	0.69	18%
0.18	0.14	0.74	0.70	5%
0.20	0.15	0.63	0.49	2%
			Average	2%
			Maximum	18%
			Minimum	-24%
			Std. Dev.	8%

	-------- Percent Error --------		
Lateral Distance (m)	Average	Maximum	Minimum
0	4%	6%	0%
0.00 to 0.10	3%	6%	-3%
0.10 to 0.15	-5%	8%	-24%
0.15 to 0.25	9%	18%	2%

Table H.11 Culvert Placed at Grade with a Discharge of 90 L/s x = 0.5 (Hole 2)

Lateral Distance (m)	Distance Above Invert (m)	Streamwise velocity measured (m/s)	Streamwise velocity predicted by Ead et al. 2000 (m/s)	Percent Error
0.00	0.15	1.11	1.05	6%
0.00	0.11	1.10	1.01	10%
0.00	0.07	1.07	0.93	16%
0.00	0.05	1.05	0.87	21%
0.00	0.13	1.11	1.03	7%
0.00	0.09	1.09	0.97	12%
0.00	0.17	1.10	1.06	4%
0.00	0.19	1.09	1.07	1%
0.05	0.19	1.09	1.02	7%
0.06	0.17	1.10	1.02	8%
0.06	0.15	1.11	1.01	10%
0.06	0.13	1.11	1.01	10%
0.06	0.11	1.10	1.00	10%
0.06	0.09	1.09	0.97	12%
0.06	0.07	1.07	0.93	15%
0.07	0.05	1.04	0.87	19%
0.11	0.18	1.09	0.94	16%
0.12	0.16	1.11	0.94	17%
0.12	0.14	1.11	0.95	16%
0.12	0.12	1.09	0.95	14%
0.13	0.10	1.04	0.95	9%
0.17	0.18	0.97	0.77	26%
0.17	0.16	1.02	0.78	31%
0.18	0.14	0.98	0.79	25%
0.20	0.19	0.78	0.55	42%
			Average	15%
			Maximum	42%
			Minimum	1%
			Std. Dev.	9%

	-------- Percent Error --------		
Lateral Distance (m)	Average	Maximum	Minimum
0	11%	21%	1%
0.00 to 0.10	11%	19%	7%
0.10 to 0.15	15%	17%	9%
0.15 to 0.25	31%	42%	25%

Table H.12 Culvert Placed at Grade with a Discharge of 90 L/s x = 1.5 (Hole 5)

Lateral Distance (m)	Distance Above Invert (m)	Streamwise velocity measured (m/s)	Streamwise velocity predicted by Ead et al. 2000 (m/s)	Percent Error
0.00	0.15	1.10	1.05	5%
0.00	0.13	1.10	1.03	6%
0.00	0.11	1.05	1.01	4%
0.00	0.09	0.99	0.97	2%
0.00	0.07	0.90	0.93	-3%
0.00	0.05	0.80	0.87	-8%
0.00	0.17	1.02	1.06	-4%
0.00	0.19	0.95	1.07	-11%
0.05	0.19	0.91	1.02	-11%
0.06	0.17	0.98	1.02	-4%
0.06	0.15	1.03	1.01	2%
0.06	0.13	1.06	1.01	5%
0.06	0.11	1.03	1.00	3%
0.06	0.09	0.97	0.97	-1%
0.06	0.07	0.88	0.93	-5%
0.07	0.05	0.77	0.87	-11%
0.11	0.18	0.91	0.94	-3%
0.12	0.16	0.98	0.94	4%
0.12	0.14	1.01	0.95	7%
0.12	0.12	1.01	0.95	6%
0.13	0.10	0.97	0.95	2%
0.13	0.08	0.85	0.94	-10%
0.17	0.18	0.90	0.77	16%
0.17	0.16	0.92	0.78	18%
0.18	0.14	0.89	0.79	13%
0.19	0.12	0.81	0.79	2%
0.20	0.19	0.79	0.55	44%
0.21	0.17	0.75	0.54	39%
			Average	4%
			Maximum	44%
			Minimum	-11%
			Std. Dev.	13%

	-------- Percent Error --------		
Lateral Distance (m)	Average	Maximum	Minimum
0	-1%	6%	-11%
0.00 to 0.10	-3%	5%	-11%
0.10 to 0.15	1%	7%	-10%
0.15 to 0.25	22%	44%	2%

Table H.13 Culvert Placed at Grade with a Discharge of 90 L/s x = 4.0 (Hole 8)

Lateral Distance (m)	Distance Above Invert (m)	Streamwise velocity measured (m/s)	Streamwise velocity predicted by Ead et al. 2000 (m/s)	Percent Error
0.00	0.03	0.68	0.78	-13%
0.00	0.05	0.77	0.87	-11%
0.00	0.07	0.83	0.93	-10%
0.00	0.09	0.89	0.97	-8%
0.00	0.11	0.96	1.01	-5%
0.00	0.13	1.01	1.03	-2%
0.00	0.15	1.04	1.05	-1%
0.00	0.17	1.06	1.06	0%
0.00	0.19	1.05	1.07	-2%
0.05	0.19	1.05	1.02	3%
0.06	0.17	1.05	1.02	4%
0.06	0.15	1.04	1.01	3%
0.06	0.13	0.99	1.01	-2%
0.06	0.11	0.95	1.00	-5%
0.06	0.09	0.88	0.97	-10%
0.06	0.07	0.81	0.93	-13%
0.07	0.05	0.76	0.87	-13%
0.11	0.18	1.06	0.94	14%
0.12	0.16	1.05	0.94	11%
0.12	0.14	1.03	0.95	8%
0.12	0.12	0.97	0.95	1%
0.13	0.10	0.89	0.95	-7%
0.13	0.08	0.78	0.94	-17%
0.17	0.18	0.97	0.77	26%
0.17	0.16	0.90	0.78	15%
0.18	0.14	0.80	0.79	1%
0.20	0.19	0.81	0.55	46%
0.21	0.17	0.74	0.54	38%
			Average	2%
			Maximum	46%
			Minimum	-17%
			Std. Dev.	15%

	-------- Percent Error --------		
Lateral Distance (m)	Average	Maximum	Minimum
0	-6%	0%	-13%
0.00 to 0.10	-4%	4%	-13%
0.10 to 0.15	2%	14%	-13%
0.15 to 0.25	25%	46%	-17%

Table H.14 Culvert Placed at Grade with a Discharge of 90 L/s x = 6.5 (Hole 11)

Lateral Distance (m)	Distance Above Invert (m)	Streamwise velocity measured (m/s)	Streamwise velocity predicted by Ead et al. 2000 (m/s)	Percent Error
0.00	0.15	1.10	1.05	5%
0.00	0.13	1.09	1.03	6%
0.00	0.11	1.06	1.01	5%
0.00	0.09	1.01	0.97	4%
0.00	0.07	0.93	0.93	1%
0.00	0.05	0.87	0.87	0%
0.00	0.17	1.10	1.06	4%
0.00	0.19	1.07	1.07	0%
0.05	0.19	1.07	1.02	5%
0.06	0.17	1.09	1.02	7%
0.06	0.15	1.08	1.01	7%
0.06	0.13	1.06	1.01	4%
0.06	0.11	1.02	1.00	2%
0.06	0.09	0.96	0.97	-1%
0.06	0.07	0.88	0.93	-5%
0.07	0.05	0.80	0.87	-9%
0.11	0.18	1.06	0.94	14%
0.12	0.16	1.02	0.94	8%
0.12	0.14	1.00	0.95	5%
0.12	0.12	0.92	0.95	-3%
0.13	0.10	0.87	0.95	-9%
0.13	0.08	0.78	0.94	-18%
0.13	0.06	0.57	0.89	-36%
0.17	0.18	0.89	0.77	16%
0.17	0.16	0.84	0.78	7%
0.18	0.14	0.80	0.79	2%
0.20	0.19	0.75	0.55	35%
0.21	0.17	0.68	0.54	26%
			Average	3%
			Maximum	35%
			Minimum	-36%
			Std. Dev.	13%

	-------- Percent Error --------		
Lateral Distance (m)	Average	Maximum	Minimum
0	3%	6%	0%
0.00 to 0.10	1%	7%	-9%
0.10 to 0.15	-5%	14%	-36%
0.15 to 0.25	17%	35%	2%

Table H.15 Culvert Placed at Grade with a Discharge of 90 L/s x = 7.5 (Hole 14)

Lateral Distance (m)	Distance Above Invert (m)	Streamwise velocity measured (m/s)	Streamwise velocity predicted by Ead et al. 2000 (m/s)	Percent Error
0.00	0.15	1.13	1.05	8%
0.00	0.13	1.13	1.03	10%
0.00	0.11	1.11	1.01	11%
0.00	0.09	1.07	0.97	10%
0.00	0.07	1.01	0.93	9%
0.00	0.05	0.93	0.87	7%
0.00	0.17	1.12	1.06	6%
0.00	0.19	1.10	1.07	3%
0.05	0.19	1.09	1.02	7%
0.06	0.17	1.11	1.02	9%
0.06	0.15	1.11	1.01	9%
0.06	0.13	1.09	1.01	8%
0.06	0.11	1.06	1.00	6%
0.06	0.09	1.01	0.97	3%
0.06	0.07	0.95	0.93	3%
0.07	0.05	0.88	0.87	0%
0.11	0.18	1.07	0.94	14%
0.12	0.16	1.04	0.94	10%
0.12	0.14	0.99	0.95	4%
0.12	0.12	0.96	0.95	0%
0.13	0.10	0.89	0.95	-7%
0.13	0.08	0.82	0.94	-13%
0.17	0.18	0.91	0.77	18%
0.17	0.16	0.86	0.78	10%
0.18	0.14	0.78	0.79	-1%
0.20	0.19	0.78	0.55	41%
0.21	0.17	0.69	0.54	29%
			Average	8%
			Maximum	41%
			Minimum	-13%
			Std. Dev.	10%

	-------- Percent Error --------		
Lateral Distance (m)	Average	Maximum	Minimum
0	8%	11%	3%
0.00 to 0.10	6%	9%	0%
0.10 to 0.15	2%	14%	-13%
0.15 to 0.25	19%	41%	-1%

APPENDIX I

Cross Section Data

Table I.1. Culvert Placed at Grade with a Discharge of 50 L/s

x (m)	y (m)	z (m)	$\bar{u}$ (m/s)	$\bar{v}$ (m/s)	$\bar{w}$ (m/s)	$RMS_{u'}$ (m/s)	$RMS_{v'}$ (m/s)	$RMS_{w'}$ (m/s)
0.5	0.00	0.15	0.919	-0.048	-0.025	0.020	0.031	0.036
(Hole 2)	0.00	0.12	0.912	-0.049	-0.017	0.020	0.030	0.033
	0.00	0.11	0.916	-0.047	-0.016	0.020	0.032	0.033
	0.00	0.09	0.920	-0.043	-0.020	0.024	0.033	0.030
	0.00	0.07	0.913	-0.034	-0.010	0.043	0.060	0.027
	0.00	0.05	0.899	-0.032	-0.017	0.033	0.042	0.023
	0.00	0.03	0.808	-0.040	-0.017	0.107	0.088	0.035
	-0.06	0.12	0.879	-0.057	-0.035	0.094	0.089	0.035
	-0.06	0.10	0.886	-0.044	-0.032	0.094	0.091	0.034
	-0.06	0.08	0.884	-0.024	-0.029	0.094	0.089	0.030
	-0.07	0.06	0.854	-0.001	-0.036	0.099	0.089	0.031
	-0.07	0.04	0.759	-0.015	-0.040	0.117	0.097	0.038
	-0.12	0.13	0.867	-0.040	-0.049	0.108	0.102	0.041
	-0.12	0.11	0.865	-0.039	-0.052	0.108	0.100	0.042
	-0.13	0.09	0.846	-0.041	-0.039	0.111	0.095	0.045
	-0.14	0.05	0.637	0.202	0.083	0.190	0.244	0.046
	-0.18	0.13	0.453	-0.008	-0.014	0.137	0.115	0.078
	-0.19	0.10	0.878	-0.071	-0.059	0.107	0.085	0.050
	-0.21	0.13	0.061	-0.013	0.010	0.076	0.036	0.017
	0.06	0.13	0.910	-0.039	-0.022	0.025	0.035	0.031
	0.06	0.12	0.914	-0.045	-0.022	0.024	0.032	0.032
	0.06	0.10	0.924	-0.053	-0.030	0.027	0.035	0.026
	0.06	0.08	0.909	-0.052	-0.031	0.047	0.058	0.027
	0.07	0.06	0.907	-0.047	-0.039	0.052	0.047	0.027
	0.12	0.13	0.867	-0.056	-0.010	0.069	0.064	0.043
	0.12	0.11	0.740	-0.064	-0.010	0.142	0.066	0.060
	0.13	0.09	0.592	-0.056	0.004	0.138	0.074	0.070
	0.14	0.05	0.293	0.026	0.028	0.088	0.053	0.030
	0.18	0.13	0.739	-0.059	0.009	0.242	0.299	0.137
	0.19	0.10	0.383	-0.073	0.018	0.112	0.084	0.044
	0.21	0.13	0.474	-0.048	0.012	0.118	0.066	0.042
1.5	0.00	0.13	0.978	-0.051	-0.015	0.063	0.069	0.033
(Hole 5)	0.00	0.11	0.996	-0.050	-0.008	0.047	0.037	0.033
	0.00	0.09	0.987	-0.042	-0.004	0.059	0.044	0.033
	0.00	0.07	0.970	-0.045	-0.012	0.085	0.047	0.036
	0.00	0.05	0.884	-0.037	-0.003	0.113	0.061	0.047
	-0.06	0.13	0.984	-0.036	-0.005	0.069	0.090	0.035
	-0.06	0.11	0.994	-0.053	-0.012	0.045	0.040	0.030
	-0.07	0.05	0.896	-0.042	-0.008	0.095	0.058	0.040
	-0.12	0.14	0.791	-0.009	-0.018	0.103	0.086	0.053
	-0.12	0.12	0.789	-0.035	-0.019	0.103	0.068	0.054
	-0.13	0.10	0.786	-0.044	-0.020	0.108	0.065	0.055
	-0.13	0.08	0.738	-0.020	-0.011	0.161	0.221	0.088
	-0.19	0.12	0.469	0.010	0.018	0.192	0.288	0.134
	-0.19	0.10	0.507	-0.049	0.028	0.238	0.068	0.055

	0.06	0.13	0.930	-0.050	0.002	0.083	0.071	0.046
	0.06	0.11	0.900	-0.048	-0.007	0.092	0.061	0.052
	0.06	0.09	0.838	-0.053	-0.003	0.113	0.069	0.058
	0.06	0.07	0.859	-0.026	-0.010	0.107	0.065	0.053
	0.07	0.05	0.816	-0.019	-0.008	0.111	0.065	0.054
	0.12	0.12	0.708	-0.036	0.018	0.127	0.074	0.066
	0.13	0.10	0.608	-0.042	0.039	0.118	0.078	0.069
	0.19	0.10	0.365	-0.034	0.006	0.115	0.064	0.033
4.0	0.00	0.13	1.004	-0.056	-0.016	0.085	0.073	0.044
(Hole 8)	0.00	0.11	1.041	-0.052	-0.020	0.065	0.046	0.041
	0.00	0.09	1.030	-0.052	-0.016	0.081	0.052	0.043
	0.00	0.07	0.908	-0.039	-0.004	0.133	0.070	0.051
	0.00	0.05	0.862	-0.051	-0.006	0.145	0.076	0.058
	-0.06	0.13	0.980	-0.050	-0.003	0.092	0.088	0.050
	-0.06	0.11	0.976	-0.059	-0.010	0.097	0.058	0.049
	-0.06	0.09	0.962	-0.051	-0.010	0.114	0.072	0.046
	-0.07	0.05	0.773	-0.053	-0.002	0.160	0.084	0.062
	-0.12	0.14	0.892	-0.057	-0.004	0.095	0.065	0.049
	-0.13	0.10	0.812	-0.050	-0.009	0.141	0.073	0.058
	-0.13	0.08	0.731	-0.048	-0.006	0.150	0.078	0.062
	-0.18	0.14	0.701	-0.059	0.002	0.139	0.087	0.057
	-0.19	0.12	0.635	-0.045	-0.010	0.225	0.280	0.129
	-0.19	0.10	0.469	-0.043	-0.010	0.211	0.076	0.060
	0.06	0.13	0.961	-0.046	-0.011	0.098	0.095	0.051
	0.06	0.11	0.999	-0.032	-0.016	0.076	0.049	0.046
	0.06	0.09	0.957	-0.045	-0.003	0.105	0.074	0.047
	0.06	0.07	0.932	-0.035	-0.010	0.121	0.065	0.049
	0.07	0.05	0.836	-0.034	-0.005	0.139	0.073	0.057
	0.12	0.14	0.844	-0.026	0.010	0.099	0.063	0.054
	0.12	0.12	0.823	-0.027	0.012	0.121	0.070	0.052
	0.13	0.10	0.814	-0.020	0.002	0.127	0.066	0.054
	0.13	0.08	0.722	-0.023	0.008	0.147	0.090	0.060
	0.13	0.06	0.545	-0.011	0.001	0.155	0.086	0.058
	0.19	0.10	0.367	-0.006	0.000	0.137	0.079	0.047
6.5	0.00	0.13	0.940	-0.038	-0.021	0.083	0.063	0.046
(Hole 11)	0.00	0.11	0.973	-0.037	-0.020	0.075	0.050	0.044
	0.00	0.09	0.986	-0.040	-0.014	0.081	0.054	0.044
	0.00	0.07	0.953	-0.045	-0.013	0.114	0.058	0.052
	0.00	0.05	0.885	-0.037	-0.007	0.125	0.070	0.053
	-0.06	0.13	0.948	-0.048	-0.007	0.082	0.057	0.047
	-0.06	0.11	0.967	-0.052	-0.010	0.083	0.055	0.046
	-0.06	0.09	0.953	-0.037	-0.008	0.100	0.068	0.047
	-0.06	0.07	0.903	-0.055	-0.012	0.119	0.078	0.050
	-0.07	0.05	0.814	-0.045	-0.006	0.139	0.076	0.060
	-0.12	0.14	0.851	-0.049	0.000	0.102	0.062	0.053
	-0.12	0.12	0.843	-0.042	-0.003	0.116	0.068	0.055
	-0.13	0.10	0.800	-0.055	-0.005	0.133	0.075	0.056
	-0.13	0.08	0.727	-0.046	-0.003	0.142	0.078	0.060
	-0.18	0.14	0.649	-0.046	0.008	0.131	0.082	0.059
	-0.19	0.12	0.600	-0.035	-0.002	0.151	0.132	0.072
	-0.19	0.10	0.476	-0.051	-0.016	0.154	0.122	0.059
	0.06	0.13	0.934	-0.027	0.000	0.085	0.061	0.051

	0.06	0.11	0.972	-0.022	-0.003	0.080	0.052	0.049
	0.06	0.09	0.955	-0.032	0.001	0.101	0.066	0.050
	0.06	0.07	0.911	-0.008	-0.005	0.118	0.088	0.050
	0.07	0.05	0.821	-0.023	-0.001	0.136	0.074	0.057
	0.12	0.14	0.851	-0.021	0.019	0.102	0.064	0.054
	0.12	0.12	0.837	-0.013	0.011	0.123	0.065	0.052
	0.13	0.10	0.798	-0.015	0.006	0.131	0.076	0.055
	0.13	0.08	0.701	-0.015	0.004	0.164	0.085	0.060
	0.13	0.06	0.543	0.043	-0.020	0.179	0.196	0.055
	0.19	0.10	0.371	0.005	-0.027	0.135	0.080	0.052
7.5	0.00	0.13	0.927	-0.038	-0.019	0.072	0.054	0.043
(Hole 14)	0.00	0.11	0.964	-0.038	-0.015	0.067	0.046	0.042
	0.00	0.09	0.971	-0.040	-0.010	0.072	0.047	0.043
	0.00	0.07	0.947	-0.037	-0.006	0.100	0.058	0.047
	0.00	0.05	0.886	-0.038	0.000	0.119	0.066	0.053
	0.00	0.03	0.766	-0.034	-0.008	0.167	0.077	0.059
	0.00	0.01	0.630	-0.039	-0.016	0.152	0.088	0.063
	-0.06	0.13	0.922	-0.046	-0.008	0.077	0.055	0.047
	-0.06	0.11	0.948	-0.053	-0.010	0.073	0.050	0.046
	-0.06	0.09	0.942	-0.051	-0.009	0.085	0.059	0.048
	-0.06	0.07	0.900	-0.050	-0.002	0.108	0.067	0.047
	-0.07	0.05	0.833	-0.045	-0.003	0.129	0.071	0.055
	-0.07	0.03	0.700	-0.041	-0.008	0.171	0.111	0.058
	-0.12	0.14	0.833	-0.046	0.006	0.094	0.060	0.053
	-0.12	0.12	0.840	-0.050	-0.001	0.106	0.066	0.053
	-0.13	0.10	0.801	-0.046	-0.001	0.121	0.070	0.056
	-0.13	0.08	0.748	-0.048	-0.002	0.135	0.073	0.058
	-0.13	0.06	0.619	-0.056	-0.014	0.187	0.098	0.054
	-0.18	0.14	0.599	-0.097	0.003	0.163	0.187	0.064
	-0.19	0.12	0.568	-0.040	0.002	0.173	0.097	0.063
	-0.19	0.10	0.498	-0.055	-0.003	0.141	0.093	0.053
	0.06	0.13	0.934	-0.031	0.008	0.077	0.054	0.047
	0.06	0.11	0.957	-0.024	0.004	0.072	0.049	0.045
	0.06	0.09	0.956	-0.028	0.002	0.083	0.053	0.045
	0.06	0.07	0.935	-0.026	0.004	0.099	0.059	0.047
	0.07	0.05	0.855	-0.025	0.005	0.127	0.068	0.054
	0.07	0.03	0.716	-0.013	-0.007	0.201	0.213	0.071
	0.12	0.14	0.855	-0.021	0.026	0.097	0.061	0.052
	0.12	0.12	0.845	-0.024	0.021	0.110	0.064	0.049
	0.13	0.10	0.812	-0.017	0.015	0.122	0.067	0.055
	0.13	0.08	0.750	-0.012	0.011	0.141	0.072	0.057
	0.13	0.06	0.629	0.001	0.000	0.160	0.104	0.059
	0.19	0.12	0.562	-0.018	0.019	0.150	0.107	0.066
	0.19	0.10	0.488	0.012	-0.009	0.138	0.087	0.055

Table I.2. Culvert Placed at Grade with a Discharge of 70 L/s

x (m)	y (m)	z (m)	$\bar{u}$ (m/s)	$\bar{v}$ (m/s)	$\bar{w}$ (m/s)	$RMS_{u'}$ (m/s)	$RMS_{v'}$ (m/s)	$RMS_{w'}$ (m/s)
0.5	0.00	0.15	1.021	-0.052	0.028	0.041	0.050	0.043
(Hole 2)	0.00	0.13	1.031	-0.048	0.028	0.036	0.046	0.040
	0.00	0.11	1.035	-0.050	0.039	0.037	0.047	0.038
	0.00	0.09	1.034	-0.050	0.042	0.038	0.050	0.034
	0.00	0.07	1.015	-0.054	0.043	0.048	0.053	0.032
	0.00	0.05	0.922	-0.055	0.034	0.104	0.061	0.039
	-0.06	0.15	1.027	-0.079	0.011	0.046	0.054	0.040
	-0.06	0.13	1.035	-0.077	0.018	0.045	0.052	0.040
	-0.06	0.11	1.040	-0.074	0.019	0.044	0.052	0.038
	-0.06	0.09	1.037	-0.070	0.030	0.046	0.052	0.034
	-0.06	0.07	1.014	-0.047	0.041	0.051	0.055	0.031
	-0.07	0.05	0.948	-0.015	0.035	0.099	0.096	0.036
	-0.12	0.16	0.997	-0.081	-0.020	0.095	0.095	0.062
	-0.12	0.14	1.035	-0.087	-0.033	0.068	0.068	0.045
	-0.12	0.12	1.042	-0.082	-0.032	0.057	0.062	0.038
	-0.13	0.10	1.025	-0.056	-0.031	0.065	0.065	0.042
	-0.17	0.16	0.771	-0.118	-0.013	0.164	0.124	0.102
	-0.18	0.14	0.921	-0.121	-0.003	0.129	0.119	0.087
	-0.19	0.12	0.904	-0.116	-0.010	0.158	0.106	0.076
	-0.19	0.10	0.653	-0.077	0.012	0.241	0.140	0.075
	-0.20	0.15	0.833	-0.160	0.010	0.188	0.110	0.084
	0.06	0.15	1.021	-0.024	0.037	0.043	0.051	0.040
	0.06	0.13	1.029	-0.045	0.032	0.045	0.053	0.039
	0.06	0.11	1.019	-0.060	0.027	0.057	0.062	0.039
	0.06	0.09	0.979	-0.079	0.005	0.087	0.073	0.042
	0.06	0.07	0.932	-0.074	-0.015	0.104	0.075	0.045
	0.07	0.05	0.916	-0.038	-0.029	0.117	0.107	0.044
	0.12	0.16	1.003	0.005	0.036	0.070	0.070	0.049
	0.12	0.14	0.948	-0.011	0.044	0.109	0.075	0.062
	0.12	0.12	0.789	-0.019	0.056	0.162	0.091	0.076
	0.13	0.10	0.631	-0.028	0.076	0.160	0.103	0.082
	0.17	0.16	0.954	0.007	0.008	0.114	0.094	0.060
	0.18	0.14	0.965	-0.003	-0.007	0.104	0.098	0.059
	0.19	0.12	0.942	-0.010	-0.017	0.142	0.109	0.057
	0.19	0.10	0.616	0.156	-0.046	0.285	0.368	0.074
1.5	0.00	0.15	1.047	-0.054	-0.005	0.067	0.058	0.043
(Hole 5)	0.00	0.13	1.060	-0.056	0.000	0.065	0.057	0.041
	0.00	0.11	1.065	-0.052	0.009	0.064	0.056	0.037
	0.00	0.09	1.047	-0.046	0.008	0.074	0.061	0.039
	0.00	0.07	1.009	-0.038	0.007	0.090	0.069	0.042
	0.00	0.05	0.941	-0.033	0.006	0.116	0.076	0.049
	-0.06	0.15	1.031	-0.066	-0.012	0.078	0.067	0.050
	-0.06	0.13	1.054	-0.066	-0.008	0.071	0.063	0.046
	-0.06	0.11	1.053	-0.059	-0.003	0.074	0.066	0.046
	-0.06	0.09	1.006	-0.044	0.000	0.101	0.075	0.050
	-0.06	0.07	0.906	-0.029	0.006	0.139	0.090	0.062
	-0.07	0.05	0.818	-0.034	0.010	0.159	0.105	0.066
	-0.12	0.16	0.946	-0.070	-0.022	0.103	0.084	0.065
	-0.12	0.14	0.966	-0.070	-0.015	0.104	0.082	0.064

	-0.12	0.12	0.925	-0.061	-0.006	0.130	0.088	0.066
	-0.13	0.10	0.848	-0.049	-0.002	0.159	0.098	0.072
	-0.17	0.16	0.860	-0.076	-0.017	0.107	0.086	0.067
	-0.18	0.14	0.837	-0.059	-0.013	0.123	0.095	0.067
	-0.20	0.16	0.777	-0.062	-0.010	0.146	0.168	0.091
	-0.20	0.17	0.791	-0.053	0.000	0.111	0.093	0.067
	0.06	0.15	0.979	-0.045	-0.002	0.105	0.084	0.055
	0.06	0.13	0.974	-0.046	0.003	0.115	0.083	0.057
	0.06	0.11	0.946	-0.045	0.006	0.126	0.087	0.059
	0.06	0.09	0.908	-0.040	0.010	0.136	0.092	0.062
	0.06	0.07	0.870	-0.030	0.009	0.145	0.096	0.062
	0.07	0.05	0.806	-0.023	0.010	0.161	0.108	0.065
	0.12	0.16	0.882	-0.027	0.010	0.105	0.076	0.061
	0.12	0.14	0.834	-0.025	0.020	0.117	0.085	0.066
	0.12	0.12	0.762	-0.029	0.031	0.126	0.094	0.068
	0.13	0.10	0.693	-0.030	0.040	0.140	0.100	0.070
	0.17	0.16	0.841	-0.013	0.001	0.110	0.080	0.057
	0.18	0.14	0.780	-0.025	0.001	0.133	0.096	0.064
	0.19	0.12	0.669	-0.026	0.006	0.178	0.110	0.066
	0.20	0.16	0.688	-0.023	0.014	0.152	0.124	0.073
	0.20	0.17	0.749	-0.016	0.007	0.163	0.178	0.096
4.0	0.00	0.15	1.084	-0.051	-0.017	0.086	0.078	0.048
(Hole 8)	0.00	0.13	1.083	-0.056	-0.013	0.085	0.063	0.050
	0.00	0.11	1.035	-0.054	-0.005	0.114	0.072	0.056
	0.00	0.09	0.982	-0.051	-0.002	0.131	0.081	0.061
	0.00	0.07	0.897	-0.047	0.002	0.157	0.090	0.068
	0.00	0.05	0.812	-0.042	0.006	0.164	0.096	0.070
	0.00	0.03	0.719	-0.032	0.007	0.186	0.129	0.069
	-0.06	0.15	1.074	-0.072	-0.015	0.079	0.059	0.049
	-0.06	0.13	1.068	-0.069	-0.009	0.089	0.061	0.051
	-0.06	0.11	1.040	-0.065	-0.005	0.109	0.068	0.055
	-0.06	0.09	0.975	-0.060	-0.002	0.132	0.080	0.061
	-0.06	0.07	0.894	-0.052	0.001	0.153	0.087	0.066
	-0.07	0.05	0.814	-0.042	-0.001	0.162	0.096	0.069
	-0.12	0.16	1.052	-0.074	-0.002	0.083	0.060	0.048
	-0.12	0.14	1.043	-0.073	-0.006	0.097	0.065	0.050
	-0.12	0.12	0.992	-0.065	-0.005	0.125	0.073	0.056
	-0.13	0.10	0.918	-0.057	-0.004	0.144	0.083	0.062
	-0.13	0.08	0.806	-0.037	0.001	0.166	0.105	0.069
	-0.13	0.06	0.613	-0.050	0.005	0.188	0.130	0.073
	-0.17	0.16	0.907	-0.064	0.000	0.127	0.076	0.060
	-0.18	0.14	0.838	-0.054	0.000	0.148	0.087	0.066
	-0.19	0.12	0.739	-0.031	0.006	0.170	0.130	0.077
	-0.19	0.10	0.572	-0.035	0.008	0.187	0.122	0.072
	-0.20	0.15	0.728	-0.044	0.003	0.160	0.117	0.076
	0.06	0.15	1.066	-0.038	-0.008	0.100	0.110	0.054
	0.06	0.13	1.047	-0.039	-0.005	0.099	0.064	0.054
	0.06	0.11	0.987	-0.038	0.002	0.125	0.076	0.060
	0.06	0.09	0.918	-0.038	0.006	0.149	0.084	0.065
	0.06	0.07	0.853	-0.039	0.006	0.156	0.090	0.069
	0.07	0.05	0.766	-0.037	0.011	0.170	0.096	0.070
	0.12	0.16	0.988	-0.025	0.010	0.107	0.066	0.054

	0.12	0.14	0.960	-0.028	0.007	0.125	0.073	0.058
	0.12	0.12	0.878	-0.029	0.013	0.147	0.083	0.064
	0.13	0.10	0.821	-0.031	0.011	0.159	0.088	0.067
	0.13	0.08	0.733	-0.028	0.010	0.186	0.150	0.077
	0.17	0.16	0.827	-0.016	0.018	0.154	0.079	0.062
	0.18	0.14	0.736	-0.032	0.023	0.162	0.091	0.070
	0.19	0.10	0.619	-0.032	0.014	0.190	0.129	0.077
	0.20	0.15	0.647	-0.034	0.026	0.189	0.123	0.076
6.5	0.00	0.15	1.023	-0.039	-0.022	0.086	0.066	0.049
(Hole 11)	0.00	0.13	1.046	-0.040	-0.014	0.088	0.067	0.049
	0.00	0.11	1.039	-0.040	-0.008	0.099	0.070	0.051
	0.00	0.09	0.992	-0.040	-0.003	0.124	0.079	0.058
	0.00	0.07	0.943	-0.039	0.004	0.143	0.088	0.062
	0.00	0.05	0.842	-0.034	0.004	0.172	0.097	0.067
	-0.06	0.15	1.035	-0.053	-0.010	0.086	0.065	0.049
	-0.06	0.13	1.035	-0.051	-0.008	0.096	0.069	0.051
	-0.06	0.11	1.010	-0.050	-0.004	0.112	0.076	0.055
	-0.06	0.09	0.948	-0.047	0.001	0.137	0.085	0.062
	-0.06	0.07	0.895	-0.045	0.002	0.150	0.092	0.065
	-0.07	0.05	0.803	-0.041	0.006	0.170	0.105	0.069
	-0.12	0.16	0.961	-0.051	0.003	0.122	0.083	0.057
	-0.12	0.14	0.933	-0.050	-0.002	0.130	0.088	0.062
	-0.12	0.12	0.888	-0.046	0.001	0.144	0.095	0.066
	-0.13	0.10	0.836	-0.049	0.003	0.155	0.099	0.068
	-0.13	0.08	0.750	-0.051	0.007	0.176	0.127	0.072
	-0.13	0.06	0.466	-0.080	0.021	0.218	0.148	0.043
	-0.17	0.16	0.757	-0.039	0.010	0.148	0.090	0.069
	-0.18	0.14	0.715	-0.045	0.010	0.159	0.105	0.072
	-0.19	0.12	0.660	-0.048	0.003	0.184	0.145	0.083
	-0.20	0.16	0.637	-0.026	0.019	0.168	0.107	0.076
	0.06	0.15	1.005	-0.026	-0.009	0.088	0.066	0.053
	0.06	0.13	1.021	-0.028	-0.005	0.091	0.066	0.051
	0.06	0.11	1.013	-0.029	-0.002	0.103	0.071	0.054
	0.06	0.09	0.971	-0.031	0.001	0.123	0.080	0.059
	0.06	0.07	0.901	-0.029	0.005	0.147	0.091	0.063
	0.07	0.05	0.808	-0.022	0.004	0.167	0.119	0.067
	0.12	0.16	0.909	-0.018	0.012	0.120	0.084	0.060
	0.12	0.14	0.904	-0.024	0.011	0.130	0.096	0.062
	0.12	0.12	0.868	-0.027	0.013	0.146	0.103	0.066
	0.13	0.10	0.806	-0.017	0.015	0.153	0.096	0.068
	0.13	0.08	0.698	-0.021	0.013	0.180	0.116	0.069
	0.13	0.06	0.555	0.001	0.004	0.179	0.136	0.069
	0.17	0.16	0.733	-0.013	0.023	0.138	0.076	0.067
	0.18	0.14	0.690	-0.012	0.024	0.147	0.088	0.068
	0.20	0.16	0.582	-0.008	0.021	0.171	0.112	0.075
7.5	0.00	0.15	1.056	-0.040	-0.024	0.077	0.066	0.048
(Hole 14)	0.00	0.13	1.070	-0.042	-0.017	0.074	0.056	0.049
	0.00	0.11	1.070	-0.043	-0.009	0.087	0.060	0.052
	0.00	0.09	1.049	-0.042	-0.004	0.104	0.067	0.055
	0.00	0.07	0.984	-0.039	0.004	0.132	0.078	0.062
	0.00	0.05	0.906	-0.040	0.009	0.156	0.089	0.067
	0.00	0.03	0.829	-0.035	0.002	0.233	0.114	0.069

	-0.06	0.15	1.053	-0.052	-0.014	0.080	0.062	0.051
	-0.06	0.13	1.053	-0.053	-0.010	0.088	0.060	0.051
	-0.06	0.11	1.034	-0.053	-0.005	0.103	0.067	0.056
	-0.06	0.09	0.995	-0.051	0.000	0.129	0.076	0.061
	-0.06	0.07	0.933	-0.048	0.004	0.149	0.083	0.067
	-0.07	0.05	0.854	-0.046	0.009	0.162	0.093	0.070
	-0.07	0.03	0.932	-0.045	-0.003	0.150	0.077	0.065
	-0.07	0.03	0.978	-0.045	-0.011	0.159	0.078	0.060
	-0.12	0.16	1.000	-0.054	0.002	0.104	0.067	0.054
	-0.12	0.14	0.967	-0.051	0.002	0.123	0.073	0.059
	-0.12	0.12	0.936	-0.050	0.004	0.137	0.080	0.063
	-0.13	0.10	0.874	-0.048	0.008	0.150	0.086	0.067
	-0.13	0.08	0.811	-0.050	0.004	0.181	0.101	0.071
	-0.17	0.16	0.821	-0.047	0.009	0.139	0.079	0.067
	-0.18	0.14	0.790	-0.045	0.007	0.149	0.089	0.069
	-0.19	0.12	0.713	-0.048	0.007	0.195	0.104	0.072
	-0.19	0.10	0.600	-0.066	-0.009	0.205	0.117	0.074
	-0.20	0.15	0.684	-0.045	0.006	0.159	0.096	0.072
	0.06	0.15	1.053	-0.028	-0.003	0.083	0.071	0.051
	0.06	0.13	1.071	-0.029	-0.002	0.077	0.057	0.049
	0.06	0.11	1.068	-0.030	0.001	0.088	0.061	0.050
	0.06	0.09	1.043	-0.032	0.005	0.106	0.066	0.053
	0.06	0.07	0.971	-0.030	0.009	0.136	0.078	0.060
	0.07	0.05	0.895	-0.026	0.010	0.152	0.090	0.065
	0.07	0.03	0.771	-0.024	0.005	0.187	0.150	0.069
	0.12	0.16	0.988	-0.023	0.018	0.100	0.064	0.056
	0.12	0.14	0.985	-0.023	0.017	0.113	0.068	0.058
	0.12	0.12	0.951	-0.025	0.017	0.128	0.075	0.061
	0.13	0.10	0.894	-0.022	0.016	0.144	0.081	0.065
	0.13	0.08	0.813	-0.012	0.014	0.182	0.093	0.068
	0.13	0.06	0.687	-0.020	0.005	0.185	0.126	0.068
	0.17	0.16	0.814	-0.011	0.029	0.142	0.074	0.065
	0.18	0.14	0.742	-0.016	0.029	0.159	0.086	0.069
	0.20	0.15	0.626	-0.004	0.018	0.187	0.113	0.075

Table I.3. Culvert Placed at Grade with a Discharge of 90 L/s

x (m)	y (m)	z (m)	$\bar{u}$ (m/s)	$\bar{v}$ (m/s)	$\bar{w}$ (m/s)	$RMS_{u'}$ (m/s)	$RMS_{v'}$ (m/s)	$RMS_{w'}$ (m/s)
0.5	0.00	0.15	1.111	-0.048	0.048	0.055	0.065	0.045
(Hole 2)	0.00	0.11	1.104	-0.052	0.066	0.057	0.065	0.045
	0.00	0.07	1.073	-0.025	0.078	0.062	0.067	0.037
	0.00	0.05	1.049	-0.034	0.062	0.069	0.073	0.034
	0.00	0.13	1.107	-0.052	0.051	0.070	0.077	0.047
	0.00	0.09	1.088	-0.039	0.076	0.073	0.074	0.042
	0.00	0.17	1.104	-0.044	0.037	0.083	0.089	0.045
	0.00	0.19	1.086	-0.045	0.033	0.102	0.103	0.051
	-0.05	0.19	1.097	-0.086	0.029	0.088	0.095	0.045
	-0.06	0.17	1.110	-0.083	0.014	0.080	0.086	0.046
	-0.06	0.15	1.121	-0.083	0.010	0.054	0.064	0.047
	-0.06	0.13	1.120	-0.085	0.019	0.055	0.064	0.047
	-0.06	0.11	1.118	-0.081	0.015	0.060	0.069	0.042

	-0.06	0.09	1.109	-0.067	0.013	0.065	0.075	0.042
	-0.06	0.07	1.090	-0.020	0.011	0.068	0.073	0.044
	-0.07	0.05	1.032	0.013	0.005	0.113	0.098	0.049
	-0.11	0.18	1.065	-0.081	-0.017	0.117	0.123	0.062
	-0.12	0.16	1.121	-0.094	-0.032	0.072	0.076	0.047
	-0.12	0.14	1.127	-0.079	-0.036	0.067	0.073	0.045
	-0.12	0.12	1.126	-0.054	-0.034	0.066	0.074	0.043
	-0.13	0.10	1.098	-0.022	-0.037	0.084	0.083	0.047
	-0.17	0.18	0.775	-0.131	-0.040	0.203	0.148	0.123
	-0.17	0.16	1.008	-0.154	-0.025	0.136	0.104	0.100
	-0.18	0.14	1.070	-0.131	-0.017	0.124	0.138	0.082
	-0.19	0.10	0.214	-0.031	-0.002	0.152	0.126	0.045
	-0.20	0.19	0.685	-0.176	0.038	0.189	0.143	0.130
	0.05	0.19	1.088	-0.016	0.036	0.090	0.096	0.046
	0.06	0.17	1.100	-0.011	0.033	0.079	0.082	0.048
	0.06	0.15	1.112	-0.012	0.036	0.056	0.063	0.047
	0.06	0.13	1.112	-0.017	0.038	0.059	0.066	0.047
	0.06	0.11	1.104	-0.014	0.036	0.066	0.070	0.043
	0.06	0.09	1.089	-0.021	0.031	0.075	0.078	0.040
	0.06	0.07	1.071	-0.030	0.014	0.082	0.081	0.042
	0.07	0.05	1.036	-0.054	0.000	0.102	0.095	0.047
	0.11	0.18	1.089	-0.003	0.010	0.097	0.103	0.054
	0.12	0.16	1.107	-0.004	-0.003	0.076	0.081	0.048
	0.12	0.14	1.107	-0.002	-0.010	0.079	0.082	0.046
	0.12	0.12	1.085	-0.017	-0.021	0.090	0.086	0.052
	0.13	0.10	1.039	-0.042	-0.015	0.113	0.096	0.066
	0.17	0.18	0.974	-0.003	0.001	0.164	0.131	0.099
	0.17	0.16	1.024	-0.001	-0.008	0.146	0.115	0.089
	0.18	0.14	0.984	0.004	-0.016	0.166	0.121	0.093
	0.20	0.19	0.784	0.022	0.037	0.189	0.140	0.119
1.5	0.00	0.15	1.097	-0.044	0.024	0.096	0.079	0.064
(Hole 5)	0.00	0.13	1.096	-0.050	0.033	0.102	0.077	0.059
	0.00	0.11	1.054	-0.050	0.040	0.123	0.085	0.059
	0.00	0.09	0.990	-0.053	0.042	0.144	0.093	0.061
	0.00	0.07	0.899	-0.048	0.044	0.165	0.103	0.067
	0.00	0.05	0.801	-0.038	0.044	0.178	0.109	0.070
	0.00	0.17	1.019	-0.041	0.000	0.117	0.093	0.072
	0.00	0.19	0.953	-0.035	-0.009	0.125	0.099	0.076
	-0.21	0.17	0.681	-0.044	0.002	0.155	0.111	0.083
	-0.20	0.19	0.718	-0.044	0.001	0.150	0.105	0.080
	-0.19	0.12	0.776	-0.067	-0.002	0.189	0.154	0.092
	-0.18	0.14	0.837	-0.057	0.000	0.156	0.106	0.084
	-0.17	0.16	0.859	-0.054	0.003	0.146	0.097	0.080
	-0.17	0.18	0.859	-0.063	-0.006	0.131	0.100	0.079
	-0.13	0.10	1.048	-0.058	-0.019	0.129	0.090	0.062
	-0.12	0.12	1.067	-0.065	-0.020	0.116	0.088	0.062
	-0.12	0.14	1.064	-0.071	-0.021	0.110	0.087	0.065
	-0.12	0.16	1.041	-0.071	-0.017	0.112	0.089	0.066
	-0.11	0.18	0.936	-0.066	-0.033	0.123	0.099	0.073
	-0.07	0.05	1.015	-0.030	0.002	0.154	0.097	0.054
	-0.06	0.07	1.084	-0.054	0.003	0.109	0.075	0.048
	-0.06	0.09	1.110	-0.071	0.007	0.089	0.069	0.047

	-0.06	0.11	1.129	-0.079	0.005	0.077	0.065	0.048
	-0.06	0.13	1.124	-0.077	0.002	0.079	0.068	0.054
	-0.06	0.15	1.095	-0.071	0.000	0.092	0.073	0.061
	-0.06	0.17	0.995	-0.057	-0.021	0.122	0.094	0.071
	-0.05	0.19	0.934	-0.049	-0.027	0.126	0.100	0.074
	0.05	0.19	0.908	-0.024	-0.018	0.140	0.107	0.082
	0.06	0.17	0.978	-0.015	-0.011	0.133	0.101	0.079
	0.06	0.15	1.034	-0.015	0.000	0.120	0.093	0.073
	0.06	0.13	1.062	-0.019	0.008	0.111	0.088	0.066
	0.06	0.11	1.035	-0.017	0.014	0.125	0.092	0.065
	0.06	0.09	0.969	-0.023	0.019	0.156	0.100	0.067
	0.06	0.07	0.884	-0.028	0.020	0.175	0.106	0.071
	0.07	0.05	0.774	-0.037	0.020	0.179	0.111	0.073
	0.11	0.18	0.907	0.001	-0.016	0.139	0.107	0.083
	0.12	0.16	0.980	0.004	-0.012	0.130	0.101	0.076
	0.12	0.14	1.013	0.000	-0.008	0.123	0.095	0.072
	0.12	0.12	1.015	-0.008	-0.008	0.123	0.094	0.066
	0.13	0.10	0.972	-0.018	-0.003	0.150	0.100	0.067
	0.13	0.08	0.851	-0.034	0.000	0.181	0.119	0.075
	0.17	0.18	0.896	0.014	0.022	0.126	0.100	0.078
	0.17	0.16	0.921	0.008	0.017	0.130	0.097	0.075
	0.18	0.14	0.894	0.000	0.014	0.150	0.099	0.073
	0.19	0.12	0.808	-0.037	0.015	0.184	0.159	0.093
	0.20	0.19	0.794	0.006	0.036	0.133	0.095	0.075
	0.21	0.17	0.749	0.000	0.026	0.151	0.116	0.081
4.0	0.00	0.15	1.041	-0.052	0.001	0.099	0.074	0.058
(Hole 8)	0.00	0.13	1.013	-0.051	0.007	0.116	0.082	0.062
	0.00	0.11	0.957	-0.050	0.014	0.134	0.090	0.067
	0.00	0.09	0.894	-0.046	0.019	0.146	0.097	0.071
	0.00	0.07	0.831	-0.041	0.018	0.155	0.099	0.072
	0.00	0.05	0.774	-0.033	0.017	0.168	0.104	0.073
	0.00	0.03	0.676	-0.021	0.022	0.183	0.123	0.071
	0.00	0.17	1.063	-0.051	-0.008	0.092	0.075	0.053
	0.00	0.19	1.046	-0.048	-0.014	0.099	0.091	0.050
	-0.21	0.17	0.773	-0.047	0.002	0.174	0.114	0.076
	-0.20	0.19	0.833	-0.059	0.002	0.155	0.097	0.069
	-0.19	0.12	0.725	-0.018	0.009	0.191	0.165	0.087
	-0.18	0.14	0.864	-0.057	-0.003	0.151	0.096	0.069
	-0.17	0.16	0.918	-0.062	0.001	0.144	0.088	0.065
	-0.17	0.18	0.981	-0.072	0.003	0.122	0.086	0.057
	-0.13	0.08	0.829	-0.038	-0.005	0.170	0.121	0.068
	-0.13	0.10	0.920	-0.051	-0.005	0.149	0.097	0.062
	-0.12	0.12	1.000	-0.061	-0.006	0.122	0.101	0.055
	-0.12	0.14	1.049	-0.073	-0.005	0.114	0.103	0.050
	-0.12	0.16	1.057	-0.076	-0.004	0.101	0.080	0.050
	-0.11	0.18	1.054	-0.076	-0.003	0.093	0.078	0.049
	-0.07	0.05	0.820	-0.034	0.000	0.170	0.100	0.068
	-0.06	0.07	0.903	-0.045	0.004	0.161	0.094	0.067
	-0.06	0.09	0.947	-0.054	0.003	0.148	0.088	0.063
	-0.06	0.11	0.999	-0.061	0.000	0.121	0.081	0.059
	-0.06	0.13	1.030	-0.067	-0.001	0.109	0.075	0.056
	-0.06	0.15	1.062	-0.068	-0.008	0.091	0.071	0.053

	-0.06	0.17	1.046	-0.067	-0.010	0.092	0.075	0.051
	-0.05	0.19	1.032	-0.062	-0.015	0.094	0.078	0.049
	0.05	0.19	1.050	-0.037	0.002	0.112	0.121	0.055
	0.06	0.17	1.052	-0.031	0.007	0.099	0.078	0.053
	0.06	0.15	1.045	-0.033	0.011	0.100	0.071	0.056
	0.06	0.13	0.988	-0.026	0.014	0.121	0.078	0.062
	0.06	0.11	0.948	-0.027	0.017	0.138	0.086	0.064
	0.06	0.09	0.880	-0.027	0.021	0.157	0.093	0.070
	0.06	0.07	0.807	-0.030	0.026	0.169	0.099	0.073
	0.07	0.05	0.756	-0.037	0.020	0.175	0.102	0.072
	0.11	0.18	1.062	-0.022	0.020	0.097	0.079	0.048
	0.12	0.16	1.050	-0.017	0.016	0.110	0.088	0.050
	0.12	0.14	1.029	-0.027	0.013	0.127	0.112	0.054
	0.12	0.12	0.967	-0.031	0.009	0.148	0.102	0.058
	0.13	0.10	0.887	-0.032	0.002	0.165	0.099	0.061
	0.13	0.08	0.780	-0.045	0.010	0.187	0.139	0.072
	0.17	0.18	0.972	-0.015	0.023	0.129	0.087	0.059
	0.17	0.16	0.901	-0.020	0.022	0.147	0.085	0.065
	0.18	0.14	0.798	-0.026	0.024	0.163	0.099	0.072
	0.20	0.19	0.809	-0.016	0.025	0.152	0.088	0.070
	0.21	0.17	0.741	-0.020	0.022	0.171	0.123	0.080
6.5	-0.21	0.17	0.726	-0.040	0.014	0.173	0.114	0.080
(Hole 11)	-0.20	0.19	0.799	-0.048	0.008	0.160	0.095	0.074
	-0.19	0.10	0.589	-0.054	-0.010	0.186	0.126	0.075
	-0.19	0.12	0.686	-0.043	0.015	0.196	0.166	0.099
	-0.18	0.14	0.825	-0.049	0.008	0.164	0.100	0.076
	-0.17	0.16	0.885	-0.049	0.007	0.159	0.094	0.075
	-0.17	0.18	0.938	-0.054	0.007	0.143	0.089	0.069
	-0.13	0.08	0.824	-0.047	0.001	0.174	0.113	0.074
	-0.13	0.10	0.930	-0.054	-0.002	0.154	0.094	0.069
	-0.12	0.12	0.993	-0.056	-0.001	0.142	0.092	0.066
	-0.12	0.14	1.045	-0.058	-0.001	0.127	0.081	0.060
	-0.12	0.16	1.078	-0.062	0.000	0.110	0.075	0.056
	-0.11	0.18	1.106	-0.062	0.003	0.095	0.072	0.052
	-0.07	0.05	0.859	-0.043	0.003	0.167	0.098	0.072
	-0.06	0.07	0.952	-0.051	-0.001	0.151	0.089	0.067
	-0.06	0.09	1.027	-0.054	-0.004	0.134	0.082	0.061
	-0.06	0.11	1.083	-0.059	-0.005	0.108	0.072	0.056
	-0.06	0.13	1.124	-0.062	-0.009	0.087	0.064	0.051
	-0.06	0.15	1.130	-0.063	-0.011	0.079	0.060	0.049
	-0.06	0.17	1.122	-0.061	-0.013	0.080	0.063	0.048
	-0.05	0.19	1.104	-0.058	-0.015	0.089	0.075	0.050
	0.00	0.15	1.098	-0.050	-0.016	0.081	0.059	0.055
	0.00	0.13	1.093	-0.050	-0.010	0.095	0.064	0.056
	0.00	0.11	1.055	-0.050	-0.004	0.118	0.071	0.062
	0.00	0.09	1.009	-0.048	0.001	0.142	0.079	0.066
	0.00	0.07	0.934	-0.044	0.005	0.157	0.089	0.072
	0.00	0.05	0.870	-0.037	0.007	0.169	0.094	0.073
	0.00	0.17	1.104	-0.046	-0.025	0.079	0.062	0.050
	0.00	0.19	1.074	-0.044	-0.034	0.085	0.074	0.049
	0.05	0.19	1.071	-0.034	-0.013	0.098	0.099	0.055
	0.06	0.17	1.089	-0.032	-0.008	0.086	0.068	0.053

	0.06	0.15	1.082	-0.036	-0.003	0.093	0.065	0.056
	0.06	0.13	1.055	-0.036	-0.001	0.113	0.071	0.061
	0.06	0.11	1.024	-0.036	0.002	0.135	0.078	0.064
	0.06	0.09	0.964	-0.033	0.007	0.151	0.086	0.069
	0.06	0.07	0.885	-0.030	0.011	0.169	0.093	0.073
	0.07	0.05	0.797	-0.028	0.012	0.181	0.105	0.074
	0.11	0.18	1.063	-0.025	0.014	0.103	0.071	0.054
	0.12	0.16	1.024	-0.024	0.012	0.132	0.080	0.059
	0.12	0.14	1.002	-0.026	0.011	0.143	0.085	0.061
	0.12	0.12	0.922	-0.026	0.015	0.166	0.093	0.070
	0.13	0.10	0.865	-0.025	0.013	0.171	0.097	0.071
	0.13	0.08	0.775	-0.031	0.012	0.200	0.130	0.075
	0.13	0.06	0.571	-0.014	0.004	0.199	0.146	0.053
	0.17	0.18	0.892	-0.023	0.024	0.152	0.087	0.069
	0.17	0.16	0.839	-0.022	0.022	0.160	0.087	0.073
	0.18	0.14	0.803	-0.017	0.021	0.170	0.093	0.072
	0.20	0.19	0.748	-0.015	0.025	0.154	0.086	0.074
	0.21	0.17	0.677	-0.019	0.025	0.174	0.131	0.087
7.5	-0.21	0.17	0.730	-0.033	0.015	0.183	0.119	0.081
(Hole 14)	-0.20	0.19	0.803	-0.049	0.007	0.159	0.098	0.075
	-0.19	0.12	0.755	-0.046	0.003	0.219	0.114	0.079
	-0.18	0.14	0.838	-0.046	0.014	0.175	0.106	0.077
	-0.17	0.16	0.881	-0.045	0.012	0.161	0.099	0.074
	-0.17	0.18	0.930	-0.048	0.010	0.148	0.091	0.070
	-0.13	0.08	0.848	-0.055	0.005	0.194	0.118	0.073
	-0.13	0.10	0.940	-0.049	0.008	0.161	0.099	0.069
	-0.12	0.12	1.007	-0.052	0.006	0.145	0.093	0.066
	-0.12	0.14	1.054	-0.054	0.003	0.130	0.086	0.062
	-0.12	0.16	1.091	-0.056	0.002	0.115	0.080	0.058
	-0.11	0.18	1.111	-0.056	0.002	0.097	0.073	0.052
	-0.07	0.05	0.896	-0.047	0.008	0.169	0.104	0.072
	-0.06	0.07	1.004	-0.048	0.002	0.146	0.094	0.066
	-0.06	0.09	1.077	-0.053	-0.001	0.124	0.082	0.059
	-0.06	0.11	1.121	-0.055	-0.003	0.109	0.074	0.055
	-0.06	0.13	1.145	-0.056	-0.006	0.092	0.068	0.051
	-0.06	0.15	1.154	-0.057	-0.011	0.080	0.063	0.048
	-0.06	0.17	1.136	-0.056	-0.015	0.079	0.063	0.047
	-0.05	0.19	1.113	-0.037	-0.012	0.124	0.166	0.059
	0.00	0.05	0.928	-0.038	0.012	0.171	0.099	0.072
	0.00	0.07	1.014	-0.042	0.006	0.149	0.089	0.066
	0.00	0.09	1.071	-0.046	0.000	0.129	0.081	0.061
	0.00	0.11	1.115	-0.045	-0.004	0.106	0.074	0.056
	0.00	0.13	1.133	-0.045	-0.010	0.091	0.067	0.052
	0.00	0.15	1.132	-0.044	-0.017	0.081	0.064	0.050
	0.00	0.17	1.123	-0.043	-0.027	0.076	0.061	0.048
	0.00	0.19	1.100	-0.043	-0.034	0.126	0.171	0.053
	0.05	0.19	1.087	-0.035	-0.006	0.118	0.145	0.061
	0.06	0.17	1.109	-0.030	-0.004	0.085	0.068	0.052
	0.06	0.15	1.111	-0.032	-0.002	0.088	0.065	0.053
	0.06	0.13	1.094	-0.034	0.001	0.106	0.070	0.057
	0.06	0.11	1.065	-0.035	0.005	0.122	0.077	0.060
	0.06	0.09	1.005	-0.034	0.010	0.141	0.086	0.066

	0.06	0.07	0.954	-0.029	0.015	0.158	0.092	0.068
	0.07	0.05	0.876	-0.031	0.016	0.173	0.107	0.071
	0.11	0.18	1.071	-0.025	0.022	0.106	0.074	0.054
	0.12	0.16	1.038	-0.026	0.018	0.132	0.081	0.060
	0.12	0.14	0.993	-0.027	0.019	0.145	0.087	0.065
	0.12	0.12	0.956	-0.024	0.021	0.155	0.093	0.069
	0.13	0.10	0.891	-0.020	0.022	0.166	0.097	0.072
	0.13	0.08	0.818	-0.026	0.013	0.213	0.109	0.069
	0.17	0.18	0.907	-0.017	0.029	0.147	0.086	0.067
	0.17	0.16	0.861	-0.017	0.032	0.166	0.090	0.071
	0.18	0.14	0.780	-0.020	0.035	0.187	0.104	0.076
	0.20	0.19	0.778	-0.007	0.025	0.153	0.085	0.071
	0.21	0.17	0.694	-0.018	0.028	0.198	0.099	0.075

Table I.4. Culvert Placed at an Embedment of 0.1D with a Discharge of 50 L/s

x (m)	y (m)	z (m)	$\bar{u}$ (m/s)	$\bar{v}$ (m/s)	$\bar{w}$ (m/s)	$RMS_{u'}$ (m/s)	$RMS_{v'}$ (m/s)	$RMS_{w'}$ (m/s)
0.5	-0.19	0.11	0.513	-0.035	0.008	0.149	0.097	0.060
(Hole 2)	-0.18	0.13	0.456	-0.021	-0.003	0.116	0.072	0.056
	-0.13	0.07	0.672	0.013	-0.001	0.129	0.191	0.069
	-0.13	0.09	0.719	-0.038	-0.025	0.073	0.058	0.032
	-0.12	0.11	0.742	-0.011	-0.031	0.059	0.052	0.033
	-0.12	0.13	0.750	-0.013	-0.028	0.048	0.051	0.032
	-0.12	0.15	0.761	-0.013	-0.021	0.036	0.035	0.029
	-0.07	0.04	0.639	-0.023	0.007	0.092	0.051	0.042
	-0.07	0.06	0.704	-0.026	-0.007	0.070	0.052	0.032
	-0.06	0.08	0.734	-0.019	-0.002	0.062	0.050	0.031
	-0.06	0.10	0.768	-0.020	-0.009	0.034	0.034	0.027
	-0.06	0.12	0.773	-0.022	-0.012	0.025	0.030	0.027
	-0.06	0.14	0.776	-0.024	-0.007	0.023	0.029	0.025
	0.00	0.02	0.587	-0.023	0.013	0.082	0.055	0.038
	0.00	0.04	0.645	-0.009	0.016	0.068	0.048	0.037
	0.00	0.06	0.685	-0.003	0.014	0.067	0.056	0.036
	0.00	0.08	0.728	-0.006	0.006	0.054	0.039	0.033
	0.00	0.10	0.764	-0.009	-0.004	0.038	0.036	0.027
	0.00	0.12	0.778	-0.012	-0.006	0.028	0.032	0.026
	0.00	0.14	0.785	-0.015	0.004	0.028	0.034	0.025
	0.06	0.14	0.780	-0.020	0.009	0.038	0.052	0.028
	0.06	0.12	0.784	-0.016	-0.010	0.027	0.031	0.026
	0.06	0.10	0.778	-0.018	-0.008	0.027	0.031	0.024
	0.06	0.08	0.767	-0.023	-0.004	0.038	0.039	0.026
	0.07	0.06	0.741	-0.035	-0.007	0.053	0.057	0.025
	0.07	0.04	0.701	-0.022	-0.014	0.060	0.053	0.031
	0.12	0.15	0.762	-0.006	0.004	0.040	0.068	0.027
	0.12	0.13	0.769	-0.032	-0.002	0.028	0.034	0.025
	0.12	0.11	0.770	-0.036	-0.007	0.043	0.050	0.029
	0.13	0.09	0.752	-0.028	-0.012	0.064	0.044	0.029
	0.13	0.07	0.686	-0.025	-0.009	0.095	0.053	0.041
	0.18	0.13	0.681	-0.021	-0.006	0.090	0.045	0.036
1.5	-0.19	0.10	0.303	-0.045	-0.011	0.283	0.094	0.051
(Hole 5)	-0.19	0.12	0.570	-0.038	0.012	0.126	0.114	0.063

	-0.18	0.14	0.612	-0.057	0.001	0.094	0.062	0.051
	-0.13	0.08	0.667	-0.036	-0.006	0.130	0.122	0.056
	-0.13	0.10	0.728	-0.054	-0.010	0.105	0.054	0.043
	-0.12	0.14	0.738	-0.045	-0.013	0.075	0.062	0.050
	-0.12	0.16	0.705	-0.038	-0.012	0.088	0.057	0.050
	-0.07	0.05	0.610	-0.026	0.011	0.122	0.069	0.054
	-0.06	0.07	0.702	-0.042	0.000	0.119	0.061	0.045
	-0.06	0.11	0.803	-0.040	-0.010	0.052	0.039	0.034
	-0.06	0.13	0.812	-0.041	-0.016	0.042	0.036	0.032
	-0.06	0.15	0.806	-0.044	-0.015	0.040	0.037	0.031
	0.00	0.05	0.707	-0.027	-0.001	0.115	0.058	0.042
	0.00	0.09	0.807	-0.032	-0.008	0.053	0.039	0.029
	0.00	0.11	0.825	-0.034	-0.010	0.037	0.033	0.027
	0.00	0.13	0.826	-0.036	-0.013	0.032	0.031	0.027
	0.00	0.15	0.818	-0.038	-0.016	0.029	0.030	0.027
	0.06	0.15	0.814	-0.026	-0.018	0.031	0.031	0.024
	0.06	0.13	0.821	-0.030	-0.013	0.034	0.032	0.026
	0.06	0.11	0.817	-0.033	-0.012	0.041	0.035	0.025
	0.06	0.07	0.781	-0.023	-0.010	0.087	0.047	0.031
	0.07	0.05	0.714	-0.022	-0.004	0.097	0.055	0.039
	0.12	0.16	0.780	-0.019	-0.013	0.056	0.040	0.032
	0.12	0.14	0.756	-0.023	-0.011	0.081	0.055	0.038
	0.13	0.10	0.675	-0.020	0.000	0.120	0.060	0.047
	0.13	0.08	0.590	-0.018	0.007	0.126	0.070	0.052
	0.18	0.14	0.564	-0.009	0.006	0.128	0.068	0.052
	0.19	0.12	0.511	0.005	0.006	0.196	0.238	0.109
4.0	-0.19	0.11	0.457	0.008	0.014	0.177	0.207	0.096
(Hole 8)	-0.18	0.13	0.543	-0.035	0.001	0.119	0.070	0.052
	-0.13	0.07	0.545	-0.028	0.006	0.133	0.072	0.055
	-0.13	0.09	0.629	-0.036	-0.001	0.127	0.070	0.052
	-0.12	0.13	0.718	-0.039	0.000	0.099	0.059	0.045
	-0.12	0.15	0.714	-0.040	0.002	0.087	0.053	0.044
	-0.07	0.04	0.565	-0.026	0.010	0.130	0.074	0.058
	-0.07	0.06	0.614	-0.029	0.002	0.136	0.071	0.053
	-0.06	0.08	0.687	-0.032	-0.001	0.112	0.073	0.051
	-0.06	0.10	0.727	-0.035	-0.001	0.096	0.059	0.050
	-0.06	0.12	0.760	-0.039	-0.005	0.084	0.053	0.047
	-0.06	0.14	0.771	-0.040	-0.006	0.068	0.049	0.045
	0.00	0.02	0.586	-0.032	0.002	0.130	0.072	0.054
	0.00	0.04	0.662	-0.030	-0.003	0.129	0.070	0.055
	0.00	0.08	0.750	-0.029	-0.005	0.106	0.058	0.051
	0.00	0.10	0.791	-0.032	-0.009	0.083	0.051	0.046
	0.00	0.12	0.808	-0.032	-0.014	0.069	0.046	0.044
	0.00	0.14	0.802	-0.031	-0.016	0.062	0.044	0.041
	0.06	0.14	0.805	-0.020	-0.012	0.063	0.045	0.040
	0.06	0.12	0.826	-0.023	-0.012	0.065	0.045	0.039
	0.06	0.10	0.815	-0.023	-0.009	0.078	0.049	0.042
	0.06	0.08	0.779	-0.026	-0.006	0.100	0.064	0.045
	0.07	0.04	0.682	-0.025	-0.004	0.124	0.068	0.051
	0.12	0.15	0.761	-0.012	0.002	0.080	0.052	0.046
	0.12	0.13	0.768	-0.010	0.000	0.087	0.053	0.045
	0.13	0.09	0.706	-0.012	0.001	0.114	0.068	0.045

	0.13	0.07	0.619	-0.014	0.005	0.124	0.071	0.054
	0.18	0.15	0.604	-0.010	0.014	0.119	0.064	0.050
	0.18	0.13	0.570	-0.002	0.010	0.130	0.065	0.054
	0.19	0.11	0.522	-0.007	0.012	0.122	0.077	0.057
6.5	-0.19	0.11	0.443	-0.035	0.002	0.149	0.155	0.077
(Hole 11)	-0.18	0.13	0.475	-0.027	0.008	0.111	0.068	0.053
	-0.13	0.07	0.514	-0.026	0.004	0.121	0.088	0.055
	-0.13	0.09	0.567	-0.035	0.001	0.116	0.081	0.051
	-0.12	0.13	0.635	-0.033	0.000	0.096	0.059	0.049
	-0.12	0.15	0.645	-0.033	0.002	0.085	0.055	0.048
	-0.07	0.04	0.569	-0.026	0.001	0.118	0.070	0.053
	-0.07	0.06	0.629	-0.031	-0.005	0.110	0.076	0.049
	-0.06	0.08	0.664	-0.027	-0.001	0.105	0.070	0.046
	-0.06	0.10	0.706	-0.030	-0.005	0.082	0.053	0.046
	-0.06	0.12	0.725	-0.032	-0.007	0.070	0.047	0.042
	-0.06	0.14	0.720	-0.033	-0.009	0.065	0.047	0.042
	0.00	0.02	0.557	-0.025	-0.001	0.128	0.072	0.052
	0.00	0.04	0.634	-0.024	-0.001	0.112	0.070	0.050
	0.00	0.08	0.729	-0.025	-0.006	0.081	0.050	0.044
	0.00	0.10	0.758	-0.026	-0.009	0.064	0.044	0.040
	0.00	0.12	0.755	-0.026	-0.013	0.058	0.042	0.038
	0.00	0.14	0.742	-0.026	-0.016	0.057	0.042	0.038
	0.06	0.14	0.741	-0.016	-0.009	0.059	0.044	0.039
	0.06	0.12	0.753	-0.016	-0.007	0.059	0.043	0.038
	0.06	0.10	0.750	-0.020	-0.004	0.067	0.046	0.040
	0.06	0.08	0.715	-0.012	-0.003	0.091	0.063	0.041
	0.07	0.04	0.627	-0.016	-0.002	0.107	0.066	0.047
	0.12	0.15	0.697	-0.008	0.006	0.075	0.051	0.044
	0.12	0.13	0.696	-0.011	0.005	0.083	0.055	0.045
	0.12	0.11	0.634	-0.032	0.013	0.113	0.063	0.050
	0.13	0.09	0.617	-0.008	0.006	0.108	0.068	0.050
	0.13	0.07	0.566	-0.010	0.008	0.117	0.069	0.052
	0.18	0.13	0.548	0.002	0.009	0.110	0.067	0.053
	0.19	0.11	0.505	-0.004	0.010	0.116	0.075	0.054
7.5	-0.19	0.09	0.349	-0.037	-0.003	0.252	0.155	0.056
(Hole 14)	-0.19	0.11	0.448	-0.030	0.005	0.116	0.067	0.051
	-0.18	0.13	0.480	-0.030	0.008	0.106	0.064	0.051
	-0.18	0.15	0.495	-0.027	0.010	0.109	0.064	0.050
	-0.13	0.07	0.518	-0.032	0.006	0.110	0.066	0.052
	-0.13	0.09	0.570	-0.033	0.004	0.100	0.064	0.050
	-0.12	0.11	0.601	-0.029	0.003	0.095	0.066	0.049
	-0.12	0.13	0.634	-0.033	0.003	0.084	0.054	0.046
	-0.12	0.15	0.632	-0.032	0.002	0.079	0.051	0.046
	-0.07	0.02	0.496	-0.026	-0.001	0.199	0.102	0.056
	-0.07	0.04	0.585	-0.036	0.003	0.106	0.067	0.050
	-0.07	0.06	0.633	-0.033	0.001	0.103	0.065	0.045
	-0.06	0.08	0.675	-0.028	0.001	0.083	0.056	0.045
	-0.06	0.10	0.701	-0.032	-0.004	0.071	0.048	0.042
	-0.06	0.12	0.710	-0.033	-0.006	0.063	0.045	0.041
	-0.06	0.14	0.698	-0.032	-0.008	0.060	0.045	0.041
	0.00	0.02	0.573	-0.023	0.004	0.113	0.067	0.050
	0.00	0.04	0.639	-0.026	0.003	0.101	0.065	0.047

	0.00	0.06	0.688	-0.023	-0.001	0.094	0.057	0.043
	0.00	0.08	0.722	-0.024	-0.004	0.070	0.045	0.040
	0.00	0.10	0.738	-0.026	-0.007	0.056	0.041	0.037
	0.00	0.12	0.734	-0.025	-0.012	0.053	0.040	0.036
	0.00	0.14	0.715	-0.023	-0.017	0.055	0.040	0.036
	0.06	0.14	0.712	-0.014	-0.008	0.057	0.042	0.038
	0.06	0.12	0.731	-0.014	-0.005	0.056	0.041	0.037
	0.06	0.10	0.729	-0.015	-0.001	0.063	0.043	0.038
	0.06	0.08	0.714	-0.017	0.001	0.079	0.055	0.041
	0.07	0.06	0.669	-0.018	0.003	0.096	0.062	0.043
	0.07	0.04	0.615	-0.013	0.006	0.106	0.066	0.047
	0.07	0.02	0.536	-0.018	-0.001	0.171	0.129	0.057
	0.12	0.15	0.679	-0.007	0.008	0.070	0.046	0.042
	0.12	0.13	0.678	-0.007	0.008	0.077	0.049	0.043
	0.12	0.11	0.644	-0.016	0.009	0.093	0.066	0.045
	0.13	0.09	0.605	-0.007	0.010	0.102	0.063	0.048
	0.13	0.07	0.561	-0.003	0.010	0.108	0.068	0.049
	0.18	0.13	0.507	-0.002	0.016	0.112	0.066	0.052
	0.19	0.11	0.460	0.002	0.013	0.116	0.076	0.053

Table I.5. Culvert Placed at an Embedment of 0.1*D* with a Discharge of 70 L/s

x (m)	y (m)	z (m)	$\bar{u}$ (m/s)	$\bar{v}$ (m/s)	$\bar{w}$ (m/s)	$RMS_{u'}$ (m/s)	$RMS_{v'}$ (m/s)	$RMS_{w'}$ (m/s)
0.5	-0.21	0.17	0.697	-0.003	-0.017	0.156	0.133	0.081
(Hole 2)	-0.18	0.13	0.516	0.008	0.022	0.166	0.116	0.097
	-0.18	0.15	0.612	0.005	0.007	0.170	0.111	0.093
	-0.17	0.17	0.727	-0.015	-0.013	0.148	0.104	0.076
	-0.13	0.07	0.637	-0.033	-0.022	0.170	0.146	0.087
	-0.13	0.09	0.609	-0.011	-0.012	0.150	0.116	0.092
	-0.12	0.11	0.619	0.013	-0.012	0.156	0.114	0.088
	-0.12	0.13	0.659	0.020	-0.015	0.163	0.107	0.084
	-0.12	0.15	0.735	0.011	-0.021	0.144	0.095	0.072
	-0.11	0.17	0.799	-0.015	-0.022	0.109	0.085	0.057
	-0.07	0.04	0.779	-0.019	-0.020	0.090	0.076	0.049
	-0.07	0.06	0.804	-0.019	-0.027	0.086	0.076	0.046
	-0.06	0.08	0.819	-0.015	-0.026	0.085	0.078	0.043
	-0.06	0.10	0.835	-0.010	-0.022	0.078	0.074	0.040
	-0.06	0.12	0.850	-0.007	-0.021	0.073	0.069	0.040
	-0.06	0.14	0.857	-0.006	-0.024	0.065	0.064	0.037
	-0.06	0.17	0.843	-0.014	-0.032	0.078	0.078	0.036
	0.00	0.04	0.773	-0.011	0.049	0.067	0.068	0.041
	0.00	0.06	0.792	-0.009	0.047	0.064	0.065	0.045
	0.00	0.08	0.823	-0.010	0.026	0.065	0.059	0.043
	0.00	0.10	0.851	-0.004	0.011	0.058	0.057	0.037
	0.00	0.12	0.865	-0.002	0.003	0.051	0.054	0.034
	0.00	0.14	0.868	-0.006	-0.009	0.047	0.053	0.035
	0.00	0.17	0.842	-0.005	-0.026	0.077	0.078	0.037
	0.06	0.17	0.842	0.002	-0.024	0.077	0.078	0.038
	0.06	0.14	0.857	0.003	-0.008	0.067	0.069	0.038
	0.06	0.12	0.861	0.003	-0.007	0.067	0.070	0.035
	0.06	0.10	0.857	0.008	-0.011	0.069	0.072	0.033

	0.06	0.08	0.839	-0.004	-0.013	0.077	0.075	0.037
	0.07	0.06	0.815	-0.019	-0.022	0.087	0.080	0.041
	0.07	0.04	0.762	-0.038	-0.024	0.112	0.086	0.049
	0.11	0.17	0.841	0.009	-0.011	0.080	0.077	0.039
	0.12	0.15	0.845	0.000	-0.011	0.078	0.075	0.041
	0.12	0.13	0.830	-0.004	-0.011	0.093	0.083	0.046
	0.12	0.11	0.797	-0.004	-0.010	0.112	0.090	0.054
	0.13	0.09	0.720	-0.013	-0.004	0.146	0.101	0.068
	0.13	0.07	0.617	-0.021	0.003	0.174	0.129	0.077
	0.17	0.17	0.804	0.010	-0.009	0.105	0.088	0.057
	0.18	0.15	0.738	-0.008	-0.010	0.138	0.096	0.070
	0.18	0.13	0.650	-0.001	-0.007	0.149	0.110	0.078
	0.21	0.17	0.756	-0.002	-0.005	0.128	0.104	0.063
1.5	-0.21	0.17	0.623	-0.008	0.004	0.148	0.090	0.069
(Hole 5)	-0.19	0.12	0.612	-0.020	0.012	0.150	0.148	0.081
	-0.18	0.14	0.623	-0.007	0.014	0.139	0.101	0.070
	-0.17	0.16	0.667	-0.008	0.008	0.131	0.097	0.069
	-0.17	0.18	0.726	-0.016	0.001	0.120	0.081	0.064
	-0.13	0.08	0.675	-0.025	0.007	0.141	0.100	0.062
	-0.13	0.10	0.720	-0.021	0.004	0.127	0.087	0.063
	-0.12	0.12	0.752	-0.016	0.004	0.110	0.082	0.062
	-0.12	0.14	0.763	-0.009	0.001	0.121	0.101	0.062
	-0.12	0.16	0.788	-0.006	-0.003	0.122	0.099	0.060
	-0.11	0.18	0.807	0.029	0.008	0.166	0.236	0.087
	-0.07	0.05	0.662	-0.012	0.018	0.143	0.106	0.059
	-0.06	0.07	0.734	-0.012	0.017	0.131	0.102	0.057
	-0.06	0.09	0.788	-0.010	0.014	0.121	0.097	0.054
	-0.06	0.11	0.832	-0.008	0.009	0.112	0.093	0.051
	-0.06	0.13	0.857	-0.008	0.005	0.109	0.092	0.048
	-0.06	0.15	0.882	-0.007	0.001	0.104	0.090	0.045
	-0.06	0.17	0.883	-0.006	0.003	0.146	0.217	0.054
	0.00	0.05	0.732	-0.016	0.011	0.132	0.099	0.053
	0.00	0.07	0.782	-0.010	0.017	0.121	0.094	0.049
	0.00	0.09	0.830	-0.004	0.019	0.106	0.089	0.046
	0.00	0.11	0.873	0.000	0.016	0.098	0.083	0.042
	0.00	0.13	0.900	-0.001	0.013	0.089	0.077	0.039
	0.00	0.15	0.918	0.001	0.007	0.081	0.074	0.036
	0.00	0.17	0.923	-0.005	0.006	0.093	0.096	0.037
	0.06	0.17	0.935	0.005	-0.002	0.065	0.060	0.033
	0.06	0.15	0.926	0.006	0.001	0.071	0.064	0.034
	0.06	0.13	0.903	0.002	0.002	0.088	0.071	0.039
	0.06	0.11	0.867	0.002	0.005	0.104	0.078	0.044
	0.06	0.09	0.814	-0.005	0.007	0.123	0.088	0.052
	0.06	0.07	0.751	-0.013	0.007	0.142	0.096	0.058
	0.07	0.05	0.696	-0.020	0.006	0.153	0.100	0.061
	0.11	0.17	0.903	0.009	-0.015	0.070	0.059	0.040
	0.12	0.16	0.889	0.003	-0.011	0.081	0.063	0.043
	0.12	0.14	0.847	-0.002	-0.005	0.101	0.073	0.049
	0.12	0.12	0.800	-0.007	-0.007	0.118	0.083	0.054
	0.13	0.10	0.739	-0.013	-0.004	0.133	0.093	0.059
	0.13	0.08	0.659	-0.020	0.001	0.150	0.126	0.068
	0.17	0.18	0.810	0.007	-0.009	0.108	0.071	0.050

	0.17	0.16	0.774	0.000	-0.007	0.125	0.078	0.056
	0.18	0.14	0.704	-0.013	-0.002	0.140	0.097	0.064
	0.21	0.17	0.692	-0.011	0.004	0.163	0.145	0.084
4.0	-0.20	0.18	0.637	-0.028	0.000	0.145	0.084	0.061
(Hole 8)	-0.19	0.12	0.581	-0.021	0.007	0.169	0.133	0.074
	-0.18	0.14	0.635	-0.021	0.007	0.157	0.094	0.065
	-0.17	0.16	0.708	-0.029	0.001	0.140	0.086	0.060
	-0.17	0.18	0.736	-0.027	0.004	0.140	0.093	0.059
	-0.13	0.08	0.616	-0.019	0.007	0.155	0.091	0.064
	-0.13	0.10	0.676	-0.016	0.006	0.152	0.095	0.065
	-0.12	0.12	0.761	-0.019	-0.002	0.146	0.100	0.059
	-0.12	0.14	0.787	-0.024	0.000	0.138	0.090	0.058
	-0.12	0.16	0.819	-0.024	-0.002	0.124	0.081	0.056
	-0.11	0.19	0.835	-0.028	-0.002	0.113	0.085	0.052
	-0.07	0.05	0.636	-0.019	0.007	0.153	0.095	0.065
	-0.06	0.07	0.705	-0.016	0.005	0.153	0.105	0.065
	-0.06	0.09	0.762	-0.015	0.003	0.147	0.099	0.062
	-0.06	0.11	0.822	-0.017	-0.002	0.135	0.093	0.058
	-0.06	0.13	0.861	-0.019	-0.005	0.125	0.086	0.055
	-0.06	0.15	0.906	-0.024	-0.010	0.104	0.077	0.050
	-0.06	0.18	0.909	-0.023	-0.014	0.096	0.076	0.048
	0.00	0.03	0.608	-0.025	0.009	0.170	0.123	0.061
	0.00	0.05	0.700	-0.016	0.005	0.159	0.101	0.064
	0.00	0.07	0.752	-0.011	0.005	0.149	0.096	0.061
	0.00	0.09	0.825	-0.011	0.001	0.136	0.088	0.058
	0.00	0.11	0.877	-0.011	-0.004	0.122	0.080	0.053
	0.00	0.13	0.919	-0.010	-0.010	0.105	0.073	0.050
	0.00	0.15	0.949	-0.015	-0.015	0.087	0.064	0.045
	0.00	0.18	0.943	-0.013	-0.023	0.089	0.076	0.046
	0.06	0.18	0.942	0.003	-0.018	0.097	0.083	0.045
	0.06	0.15	0.950	0.002	-0.010	0.101	0.080	0.044
	0.06	0.13	0.908	0.002	-0.004	0.122	0.087	0.050
	0.06	0.11	0.883	-0.001	-0.002	0.132	0.093	0.053
	0.06	0.09	0.821	-0.004	0.003	0.149	0.101	0.057
	0.06	0.07	0.775	-0.010	0.004	0.144	0.086	0.058
	0.07	0.05	0.702	-0.014	0.003	0.151	0.093	0.061
	0.11	0.19	0.901	0.009	0.001	0.105	0.087	0.049
	0.12	0.16	0.913	0.010	0.000	0.108	0.084	0.048
	0.12	0.14	0.896	0.007	-0.003	0.115	0.086	0.049
	0.12	0.12	0.845	-0.001	-0.001	0.129	0.080	0.053
	0.13	0.10	0.775	-0.003	0.001	0.138	0.088	0.059
	0.13	0.08	0.668	-0.009	0.005	0.161	0.112	0.063
	0.17	0.18	0.803	0.013	0.010	0.136	0.094	0.059
	0.17	0.16	0.753	0.008	0.007	0.150	0.095	0.063
	0.18	0.14	0.672	0.003	0.011	0.156	0.106	0.070
	0.20	0.18	0.642	0.009	0.012	0.145	0.094	0.067
6.5	-0.21	0.19	0.551	-0.016	0.016	0.138	0.090	0.066
(Hole 11)	-0.20	0.21	0.595	-0.022	0.014	0.129	0.076	0.063
	-0.19	0.12	0.567	-0.025	0.008	0.161	0.119	0.072
	-0.18	0.14	0.627	-0.020	0.010	0.148	0.095	0.067
	-0.17	0.16	0.663	-0.020	0.008	0.142	0.091	0.064
	-0.17	0.19	0.692	-0.022	0.010	0.136	0.091	0.062

	-0.16	0.20	0.703	-0.019	0.011	0.131	0.090	0.060
	-0.13	0.08	0.643	-0.021	0.002	0.148	0.097	0.062
	-0.13	0.10	0.709	-0.017	0.002	0.148	0.112	0.060
	-0.12	0.12	0.753	-0.026	0.001	0.135	0.101	0.058
	-0.12	0.14	0.796	-0.025	-0.001	0.120	0.081	0.056
	-0.12	0.16	0.806	-0.024	0.001	0.113	0.078	0.055
	-0.11	0.19	0.808	-0.023	0.001	0.108	0.081	0.053
	-0.11	0.21	0.787	-0.018	0.002	0.110	0.082	0.053
	-0.07	0.05	0.644	-0.012	0.005	0.153	0.095	0.064
	-0.06	0.07	0.714	-0.012	0.004	0.147	0.088	0.064
	-0.06	0.09	0.778	-0.018	-0.002	0.131	0.082	0.060
	-0.06	0.11	0.823	-0.017	-0.004	0.124	0.086	0.055
	-0.06	0.13	0.834	-0.020	-0.003	0.115	0.081	0.055
	-0.06	0.13	0.844	-0.018	-0.006	0.108	0.074	0.053
	-0.06	0.15	0.860	-0.021	-0.007	0.099	0.076	0.051
	-0.06	0.15	0.862	-0.021	-0.008	0.093	0.069	0.051
	-0.06	0.18	0.851	-0.020	-0.013	0.084	0.064	0.051
	-0.05	0.21	0.814	-0.011	-0.012	0.092	0.075	0.052
	0.00	0.03	0.596	-0.009	0.002	0.167	0.112	0.063
	0.00	0.05	0.666	-0.010	0.006	0.148	0.090	0.066
	0.00	0.07	0.733	-0.009	0.001	0.138	0.082	0.064
	0.00	0.09	0.775	-0.009	0.001	0.130	0.084	0.062
	0.00	0.11	0.807	-0.013	-0.001	0.128	0.088	0.059
	0.00	0.13	0.859	-0.012	-0.008	0.106	0.076	0.053
	0.00	0.15	0.870	-0.013	-0.012	0.093	0.070	0.051
	0.00	0.18	0.864	-0.012	-0.020	0.077	0.059	0.046
	0.00	0.21	0.828	-0.006	-0.019	0.088	0.073	0.047
	0.05	0.21	0.825	-0.006	-0.008	0.104	0.088	0.052
	0.06	0.18	0.853	0.000	-0.013	0.094	0.074	0.049
	0.06	0.15	0.864	-0.002	-0.007	0.101	0.074	0.051
	0.06	0.13	0.841	-0.003	-0.003	0.113	0.076	0.054
	0.06	0.11	0.809	-0.002	-0.002	0.128	0.090	0.058
	0.06	0.09	0.752	-0.001	0.001	0.143	0.096	0.061
	0.06	0.07	0.719	-0.001	0.000	0.148	0.102	0.063
	0.07	0.05	0.658	-0.003	0.001	0.159	0.105	0.063
	0.11	0.21	0.798	0.001	0.004	0.112	0.086	0.054
	0.11	0.19	0.830	0.006	0.003	0.110	0.083	0.052
	0.12	0.16	0.810	0.004	0.003	0.118	0.079	0.055
	0.12	0.14	0.778	0.002	0.003	0.134	0.096	0.057
	0.12	0.12	0.749	-0.001	0.003	0.140	0.097	0.061
	0.13	0.10	0.681	-0.001	0.006	0.156	0.092	0.063
	0.13	0.08	0.610	0.004	0.006	0.160	0.106	0.065
	0.16	0.20	0.728	-0.004	0.014	0.130	0.092	0.060
	0.17	0.19	0.715	0.005	0.012	0.140	0.095	0.064
	0.17	0.16	0.673	0.006	0.009	0.133	0.082	0.063
	0.18	0.14	0.643	0.009	0.008	0.139	0.082	0.063
	0.19	0.12	0.579	0.013	0.003	0.157	0.120	0.071
	0.20	0.21	0.594	0.009	0.017	0.133	0.082	0.065
	0.21	0.19	0.551	0.003	0.017	0.144	0.094	0.069
7.5	-0.21	0.19	0.499	-0.022	0.014	0.150	0.113	0.071
(Hole 14)	-0.20	0.21	0.526	-0.022	0.016	0.139	0.097	0.066
	-0.19	0.12	0.586	-0.027	0.008	0.143	0.095	0.065

-0.18	0.14	0.626	-0.021	0.014	0.147	0.096	0.064
-0.17	0.16	0.653	-0.020	0.014	0.138	0.093	0.063
-0.17	0.19	0.661	-0.025	0.015	0.132	0.090	0.061
-0.16	0.20	0.660	-0.023	0.018	0.132	0.089	0.059
-0.13	0.08	0.642	-0.016	0.006	0.148	0.104	0.062
-0.13	0.10	0.693	-0.018	0.009	0.142	0.092	0.060
-0.12	0.12	0.740	-0.019	0.006	0.127	0.085	0.056
-0.12	0.14	0.768	-0.020	0.006	0.119	0.078	0.055
-0.12	0.16	0.789	-0.022	0.003	0.106	0.071	0.052
-0.11	0.19	0.788	-0.025	0.007	0.101	0.075	0.051
-0.11	0.21	0.758	-0.019	0.009	0.106	0.081	0.053
-0.07	0.03	0.557	-0.016	0.008	0.177	0.137	0.062
-0.07	0.05	0.669	-0.013	0.006	0.140	0.090	0.060
-0.06	0.07	0.733	-0.014	0.004	0.138	0.094	0.057
-0.06	0.09	0.767	-0.014	0.003	0.129	0.090	0.057
-0.06	0.11	0.804	-0.017	-0.001	0.118	0.083	0.052
-0.06	0.13	0.825	-0.018	-0.002	0.107	0.079	0.051
-0.06	0.15	0.835	-0.018	-0.008	0.095	0.076	0.048
-0.06	0.18	0.818	-0.016	-0.010	0.092	0.075	0.047
-0.05	0.21	0.780	-0.006	-0.011	0.103	0.085	0.050
0.00	0.03	0.626	-0.009	0.007	0.147	0.101	0.061
0.00	0.05	0.694	-0.007	0.007	0.139	0.088	0.061
0.00	0.07	0.754	-0.008	0.004	0.127	0.081	0.057
0.00	0.09	0.800	-0.010	-0.001	0.113	0.072	0.055
0.00	0.11	0.829	-0.011	-0.003	0.101	0.066	0.052
0.00	0.13	0.850	-0.010	-0.008	0.084	0.059	0.049
0.00	0.15	0.843	-0.008	-0.013	0.096	0.082	0.047
0.00	0.18	0.828	-0.008	-0.020	0.083	0.067	0.044
0.00	0.20	0.797	-0.006	-0.024	0.096	0.078	0.045
0.05	0.21	0.796	-0.009	-0.011	0.095	0.079	0.048
0.06	0.18	0.827	-0.006	-0.011	0.086	0.069	0.046
0.06	0.15	0.849	0.000	-0.007	0.083	0.062	0.047
0.06	0.13	0.826	0.000	-0.002	0.100	0.069	0.050
0.06	0.11	0.808	-0.002	0.001	0.111	0.074	0.054
0.06	0.09	0.769	-0.003	0.003	0.123	0.080	0.057
0.06	0.07	0.718	-0.003	0.005	0.139	0.088	0.059
0.07	0.05	0.676	0.000	0.006	0.145	0.093	0.060
0.07	0.03	0.586	0.009	0.008	0.194	0.121	0.062
0.11	0.21	0.781	-0.005	0.008	0.104	0.081	0.052
0.11	0.19	0.797	0.002	0.006	0.104	0.081	0.051
0.12	0.16	0.798	0.005	0.004	0.103	0.068	0.051
0.12	0.14	0.783	0.008	0.006	0.115	0.079	0.054
0.12	0.12	0.731	0.005	0.009	0.130	0.084	0.059
0.13	0.10	0.682	0.005	0.010	0.142	0.088	0.060
0.13	0.08	0.625	0.009	0.012	0.151	0.097	0.061
0.16	0.20	0.699	0.002	0.018	0.124	0.088	0.057
0.17	0.19	0.697	0.006	0.016	0.134	0.091	0.059
0.17	0.16	0.662	0.010	0.015	0.138	0.089	0.061
0.18	0.14	0.615	0.012	0.018	0.152	0.097	0.065
0.19	0.12	0.546	-0.002	0.023	0.169	0.107	0.067
0.20	0.21	0.590	0.008	0.018	0.119	0.073	0.061
0.21	0.19	0.571	0.008	0.016	0.129	0.082	0.062

Table I.6. Culvert Placed at an Embedment of 0.1D with a Discharge of 90 L/s

x (m)	y (m)	z (m)	$\bar{u}$ (m/s)	$\bar{v}$ (m/s)	$\bar{w}$ (m/s)	$RMS_{u'}$ (m/s)	$RMS_{v'}$ (m/s)	$RMS_{w'}$ (m/s)
0.5	-0.21	0.20	0.552	-0.072	0.013	0.204	0.167	0.119
(Hole 2)	-0.20	0.22	0.549	-0.084	0.017	0.216	0.147	0.122
	-0.18	0.14	0.653	-0.053	-0.016	0.205	0.137	0.117
	-0.17	0.16	0.685	-0.041	-0.026	0.202	0.141	0.116
	-0.17	0.19	0.712	-0.054	-0.036	0.197	0.143	0.111
	-0.16	0.22	0.639	-0.065	-0.034	0.233	0.148	0.109
	-0.13	0.08	0.697	-0.023	-0.019	0.178	0.145	0.097
	-0.13	0.10	0.738	-0.015	-0.035	0.180	0.132	0.099
	-0.12	0.12	0.769	-0.017	-0.047	0.176	0.127	0.091
	-0.12	0.14	0.812	-0.027	-0.049	0.165	0.124	0.079
	-0.12	0.16	0.854	-0.042	-0.049	0.136	0.114	0.068
	-0.11	0.18	0.867	-0.058	-0.038	0.123	0.111	0.062
	-0.11	0.20	0.863	-0.061	-0.023	0.121	0.113	0.060
	-0.10	0.22	0.834	-0.072	-0.019	0.126	0.119	0.066
	-0.07	0.05	0.784	0.001	-0.017	0.136	0.122	0.077
	-0.06	0.07	0.812	-0.006	-0.022	0.132	0.119	0.074
	-0.06	0.09	0.827	-0.020	-0.018	0.131	0.116	0.073
	-0.06	0.11	0.852	-0.037	-0.017	0.124	0.111	0.065
	-0.06	0.13	0.874	-0.059	-0.007	0.113	0.107	0.057
	-0.06	0.15	0.888	-0.065	-0.008	0.105	0.097	0.052
	-0.06	0.18	0.894	-0.067	-0.005	0.097	0.094	0.048
	-0.05	0.20	0.886	-0.069	-0.003	0.096	0.092	0.046
	-0.05	0.21	0.874	-0.073	-0.002	0.096	0.094	0.044
	0.00	0.03	0.788	0.013	0.023	0.125	0.110	0.060
	0.00	0.05	0.838	0.009	0.026	0.106	0.102	0.064
	0.00	0.07	0.853	-0.015	0.034	0.100	0.100	0.065
	0.00	0.09	0.862	-0.044	0.037	0.096	0.098	0.060
	0.00	0.11	0.880	-0.058	0.041	0.091	0.094	0.052
	0.00	0.13	0.900	-0.068	0.037	0.080	0.085	0.046
	0.00	0.15	0.906	-0.065	0.036	0.075	0.077	0.044
	0.00	0.18	0.894	-0.052	0.024	0.088	0.089	0.044
	0.00	0.20	0.882	-0.058	0.019	0.086	0.085	0.043
	0.00	0.22	0.869	-0.058	0.010	0.087	0.086	0.043
	0.05	0.21	0.862	-0.019	0.021	0.096	0.090	0.043
	0.05	0.20	0.876	-0.027	0.028	0.093	0.089	0.043
	0.06	0.18	0.885	-0.025	0.033	0.091	0.088	0.044
	0.06	0.15	0.873	-0.027	0.046	0.075	0.075	0.043
	0.06	0.13	0.852	-0.028	0.059	0.082	0.079	0.051
	0.06	0.11	0.828	-0.024	0.069	0.088	0.087	0.059
	0.06	0.09	0.806	-0.035	0.068	0.096	0.094	0.062
	0.06	0.07	0.793	-0.051	0.054	0.103	0.098	0.061
	0.07	0.05	0.767	-0.052	0.034	0.113	0.102	0.058
	0.10	0.22	0.862	-0.010	0.024	0.087	0.084	0.042
	0.11	0.20	0.879	-0.013	0.023	0.090	0.088	0.045
	0.11	0.18	0.884	-0.019	0.021	0.094	0.090	0.047
	0.12	0.16	0.874	-0.023	0.006	0.098	0.095	0.049
	0.12	0.14	0.854	-0.020	0.000	0.110	0.102	0.053
	0.12	0.12	0.809	-0.026	-0.009	0.132	0.108	0.065
	0.13	0.10	0.755	-0.031	-0.004	0.160	0.118	0.081

	0.13	0.08	0.660	-0.037	0.003	0.168	0.128	0.090
	0.16	0.22	0.849	-0.011	0.015	0.106	0.093	0.059
	0.17	0.19	0.784	-0.017	0.010	0.154	0.107	0.081
	0.17	0.16	0.678	-0.019	0.012	0.177	0.128	0.096
	0.18	0.14	0.626	-0.014	0.013	0.177	0.138	0.097
	0.19	0.12	0.580	-0.018	0.009	0.186	0.154	0.100
	0.20	0.22	0.815	-0.012	0.007	0.133	0.104	0.070
	0.21	0.20	0.760	-0.027	0.002	0.161	0.116	0.081
1.5	-0.21	0.20	0.681	-0.033	-0.013	0.141	0.079	0.067
(Hole 5)	-0.20	0.22	0.724	-0.054	-0.016	0.126	0.074	0.068
	-0.19	0.12	0.673	-0.007	-0.008	0.168	0.150	0.080
	-0.18	0.14	0.757	-0.033	-0.015	0.141	0.077	0.063
	-0.17	0.16	0.800	-0.043	-0.012	0.125	0.077	0.066
	-0.17	0.19	0.816	-0.048	-0.015	0.109	0.077	0.070
	-0.16	0.22	0.796	-0.052	-0.024	0.103	0.075	0.074
	-0.13	0.06	0.662	0.010	-0.017	0.183	0.121	0.056
	-0.13	0.08	0.783	-0.001	-0.015	0.157	0.137	0.069
	-0.13	0.10	0.829	-0.020	-0.021	0.146	0.073	0.055
	-0.12	0.12	0.871	-0.024	-0.019	0.120	0.071	0.057
	-0.12	0.14	0.889	-0.038	-0.019	0.101	0.072	0.058
	-0.12	0.16	0.907	-0.052	-0.023	0.089	0.065	0.057
	-0.11	0.18	0.896	-0.053	-0.024	0.086	0.068	0.058
	-0.11	0.20	0.880	-0.053	-0.026	0.089	0.071	0.061
	-0.10	0.22	0.848	-0.049	-0.032	0.099	0.076	0.064
	-0.07	0.05	0.768	0.002	0.003	0.138	0.080	0.059
	-0.06	0.07	0.825	-0.010	0.000	0.128	0.075	0.057
	-0.06	0.09	0.860	-0.011	0.000	0.104	0.076	0.054
	-0.06	0.11	0.892	-0.032	-0.001	0.089	0.064	0.054
	-0.06	0.13	0.912	-0.044	-0.005	0.083	0.061	0.052
	-0.06	0.15	0.925	-0.053	-0.006	0.076	0.058	0.050
	-0.06	0.18	0.935	-0.059	-0.013	0.067	0.056	0.048
	-0.05	0.20	0.934	-0.059	-0.020	0.067	0.057	0.049
	-0.05	0.21	0.917	-0.053	-0.025	0.075	0.063	0.052
	0.00	0.05	0.750	-0.004	0.018	0.133	0.080	0.057
	0.00	0.09	0.830	-0.023	0.031	0.098	0.071	0.053
	0.00	0.11	0.858	-0.032	0.032	0.090	0.066	0.052
	0.00	0.13	0.886	-0.035	0.031	0.081	0.062	0.050
	0.00	0.15	0.912	-0.045	0.024	0.077	0.056	0.049
	0.00	0.18	0.939	-0.041	0.012	0.067	0.051	0.047
	0.00	0.20	0.947	-0.045	-0.001	0.061	0.048	0.047
	0.00	0.22	0.934	-0.039	-0.019	0.064	0.056	0.047
	0.05	0.21	0.947	-0.017	-0.007	0.060	0.049	0.043
	0.05	0.20	0.952	-0.016	-0.002	0.062	0.047	0.043
	0.06	0.18	0.945	-0.014	0.011	0.068	0.050	0.044
	0.06	0.15	0.916	-0.020	0.020	0.084	0.055	0.049
	0.06	0.13	0.865	-0.024	0.030	0.100	0.066	0.054
	0.06	0.11	0.820	-0.021	0.034	0.111	0.070	0.057
	0.06	0.09	0.757	-0.029	0.034	0.125	0.087	0.055
	0.06	0.07	0.704	-0.018	0.029	0.137	0.088	0.059
	0.07	0.05	0.642	-0.016	0.028	0.139	0.087	0.064
	0.10	0.22	0.934	-0.007	-0.011	0.072	0.061	0.044
	0.11	0.20	0.933	-0.004	-0.010	0.072	0.052	0.044

	0.11	0.18	0.903	-0.005	-0.002	0.090	0.059	0.049
	0.12	0.16	0.871	-0.012	0.004	0.107	0.065	0.057
	0.12	0.14	0.827	-0.009	0.009	0.121	0.074	0.060
	0.12	0.12	0.784	-0.021	0.009	0.148	0.079	0.059
	0.13	0.10	0.692	-0.011	0.014	0.158	0.081	0.063
	0.13	0.08	0.653	-0.019	0.008	0.150	0.096	0.065
	0.16	0.22	0.898	0.000	-0.015	0.084	0.055	0.049
	0.17	0.19	0.863	-0.012	-0.012	0.105	0.073	0.054
	0.17	0.16	0.794	-0.015	-0.010	0.126	0.075	0.059
	0.18	0.14	0.729	-0.012	-0.008	0.140	0.079	0.063
	0.19	0.12	0.643	-0.012	-0.004	0.148	0.086	0.064
	0.20	0.22	0.818	0.005	-0.014	0.119	0.062	0.050
	0.21	0.20	0.754	-0.007	-0.010	0.145	0.070	0.057
4.0	-0.21	0.19	0.727	-0.041	-0.002	0.148	0.073	0.058
(Hole 8)	-0.20	0.23	0.770	-0.042	0.012	0.126	0.066	0.054
	-0.19	0.12	0.641	-0.008	0.003	0.165	0.141	0.077
	-0.18	0.14	0.757	-0.033	-0.005	0.149	0.079	0.061
	-0.18	0.16	0.821	-0.044	-0.006	0.147	0.071	0.055
	-0.17	0.18	0.895	-0.037	0.001	0.108	0.072	0.051
	-0.16	0.21	0.916	-0.050	0.004	0.086	0.055	0.047
	-0.16	0.23	0.892	-0.044	0.013	0.085	0.057	0.047
	-0.13	0.07	0.702	-0.017	-0.006	0.146	0.081	0.063
	-0.13	0.09	0.801	-0.029	-0.007	0.137	0.076	0.055
	-0.12	0.13	0.913	-0.035	-0.005	0.104	0.063	0.049
	-0.12	0.15	0.954	-0.045	-0.005	0.085	0.054	0.045
	-0.11	0.18	0.963	-0.049	-0.005	0.072	0.052	0.044
	-0.11	0.21	0.953	-0.047	-0.003	0.071	0.052	0.043
	-0.10	0.23	0.891	-0.034	0.007	0.084	0.066	0.048
	-0.07	0.05	0.740	-0.010	-0.008	0.141	0.077	0.058
	-0.07	0.07	0.780	-0.027	0.000	0.136	0.077	0.054
	-0.06	0.09	0.858	-0.020	-0.005	0.124	0.075	0.052
	-0.06	0.11	0.899	-0.033	-0.005	0.107	0.061	0.052
	-0.06	0.13	0.936	-0.040	-0.008	0.093	0.057	0.050
	-0.06	0.15	0.954	-0.044	-0.007	0.085	0.053	0.048
	-0.06	0.18	0.968	-0.046	-0.012	0.071	0.049	0.045
	-0.05	0.21	0.949	-0.039	-0.014	0.073	0.052	0.046
	-0.05	0.23	0.902	-0.027	-0.007	0.085	0.067	0.047
	0.00	0.03	0.621	-0.002	0.006	0.150	0.083	0.061
	0.00	0.05	0.709	-0.008	0.003	0.144	0.078	0.062
	0.00	0.09	0.784	-0.023	0.009	0.129	0.073	0.062
	0.00	0.11	0.834	-0.029	0.005	0.117	0.070	0.060
	0.00	0.13	0.875	-0.032	0.004	0.110	0.065	0.059
	0.00	0.15	0.911	-0.033	-0.001	0.097	0.061	0.056
	0.00	0.18	0.956	-0.036	-0.008	0.083	0.051	0.051
	0.00	0.21	0.962	-0.032	-0.019	0.074	0.050	0.047
	0.00	0.23	0.912	-0.023	-0.012	0.085	0.055	0.045
	0.05	0.23	0.926	-0.022	0.001	0.085	0.066	0.047
	0.05	0.21	0.951	-0.017	-0.008	0.078	0.052	0.050
	0.06	0.18	0.937	-0.014	0.000	0.094	0.056	0.053
	0.06	0.15	0.872	-0.021	0.010	0.117	0.066	0.061
	0.06	0.13	0.822	-0.021	0.013	0.123	0.071	0.065
	0.06	0.11	0.764	-0.020	0.019	0.127	0.077	0.067

	0.06	0.09	0.706	-0.027	0.026	0.138	0.087	0.063
	0.07	0.07	0.649	-0.010	0.020	0.145	0.086	0.061
	0.07	0.05	0.616	-0.008	0.018	0.145	0.082	0.063
	0.10	0.23	0.905	-0.009	0.014	0.088	0.068	0.049
	0.11	0.21	0.933	-0.002	0.001	0.088	0.054	0.049
	0.11	0.18	0.906	-0.002	0.006	0.111	0.059	0.052
	0.12	0.15	0.830	-0.006	0.014	0.136	0.069	0.061
	0.12	0.13	0.800	-0.009	0.012	0.147	0.075	0.061
	0.13	0.09	0.637	-0.010	0.018	0.166	0.080	0.061
	0.13	0.07	0.593	-0.013	0.015	0.151	0.083	0.062
	0.16	0.23	0.877	0.002	0.014	0.093	0.058	0.049
	0.16	0.21	0.890	0.006	0.006	0.101	0.058	0.049
	0.17	0.19	0.841	-0.001	0.006	0.130	0.073	0.053
	0.18	0.14	0.692	-0.007	0.008	0.161	0.079	0.062
	0.19	0.12	0.603	-0.015	0.010	0.158	0.094	0.065
	0.20	0.23	0.788	0.008	0.017	0.123	0.071	0.055
	0.21	0.20	0.766	0.005	0.005	0.143	0.073	0.057
6.5	-0.21	0.21	0.626	-0.023	0.015	0.161	0.113	0.077
(Hole 11)	-0.20	0.23	0.698	-0.036	0.012	0.158	0.101	0.070
	-0.19	0.12	0.555	-0.017	0.015	0.183	0.160	0.088
	-0.18	0.14	0.666	-0.030	0.008	0.156	0.105	0.073
	-0.17	0.16	0.724	-0.033	0.007	0.148	0.095	0.070
	-0.17	0.19	0.782	-0.033	0.009	0.153	0.104	0.067
	-0.16	0.22	0.826	-0.038	0.007	0.141	0.097	0.062
	-0.15	0.24	0.826	-0.036	0.010	0.129	0.095	0.060
	-0.13	0.08	0.660	-0.026	-0.002	0.163	0.102	0.067
	-0.13	0.10	0.723	-0.030	-0.004	0.168	0.094	0.066
	-0.12	0.12	0.796	-0.031	-0.003	0.148	0.100	0.065
	-0.12	0.14	0.845	-0.034	-0.003	0.143	0.100	0.061
	-0.12	0.16	0.888	-0.038	-0.002	0.130	0.095	0.057
	-0.11	0.19	0.920	-0.038	-0.001	0.118	0.091	0.052
	-0.11	0.21	0.926	-0.040	0.001	0.111	0.089	0.050
	-0.10	0.24	0.893	-0.030	0.006	0.112	0.091	0.050
	-0.07	0.05	0.695	-0.020	0.000	0.160	0.106	0.066
	-0.06	0.07	0.763	-0.023	-0.002	0.155	0.100	0.065
	-0.06	0.09	0.828	-0.028	-0.006	0.141	0.090	0.061
	-0.06	0.11	0.872	-0.029	-0.006	0.136	0.095	0.059
	-0.06	0.13	0.898	-0.031	-0.007	0.129	0.095	0.055
	-0.06	0.15	0.924	-0.035	-0.009	0.116	0.090	0.052
	-0.06	0.18	0.933	-0.039	-0.013	0.104	0.082	0.048
	-0.05	0.21	0.924	-0.036	-0.016	0.102	0.085	0.047
	-0.05	0.24	0.894	-0.030	-0.015	0.109	0.092	0.049
	0.00	0.03	0.601	-0.012	0.001	0.170	0.136	0.065
	0.00	0.05	0.700	-0.016	0.001	0.161	0.107	0.066
	0.00	0.07	0.760	-0.019	0.000	0.159	0.103	0.066
	0.00	0.09	0.814	-0.021	-0.003	0.146	0.100	0.063
	0.00	0.11	0.846	-0.023	-0.006	0.142	0.097	0.061
	0.00	0.13	0.876	-0.027	-0.007	0.131	0.091	0.059
	0.00	0.15	0.902	-0.030	-0.009	0.118	0.087	0.056
	0.00	0.18	0.927	-0.032	-0.017	0.095	0.075	0.051
	0.00	0.21	0.906	-0.032	-0.029	0.104	0.083	0.049
	0.00	0.24	0.872	-0.023	-0.032	0.136	0.092	0.050

	0.05	0.24	0.868	-0.016	-0.017	0.108	0.093	0.052
	0.05	0.21	0.890	-0.017	-0.018	0.106	0.091	0.053
	0.06	0.18	0.889	-0.021	-0.009	0.116	0.090	0.056
	0.06	0.15	0.860	-0.024	-0.002	0.116	0.079	0.061
	0.06	0.13	0.834	-0.022	0.000	0.126	0.084	0.064
	0.06	0.11	0.794	-0.021	0.001	0.137	0.092	0.064
	0.06	0.09	0.758	-0.015	0.001	0.141	0.096	0.066
	0.06	0.07	0.704	-0.012	0.006	0.153	0.101	0.068
	0.07	0.05	0.644	-0.008	0.008	0.162	0.105	0.066
	0.10	0.24	0.844	-0.012	0.004	0.115	0.092	0.054
	0.11	0.21	0.857	-0.006	0.002	0.125	0.092	0.057
	0.11	0.19	0.849	-0.007	0.003	0.134	0.095	0.059
	0.12	0.16	0.801	-0.005	0.007	0.148	0.099	0.064
	0.12	0.14	0.746	-0.009	0.012	0.159	0.104	0.068
	0.12	0.12	0.705	-0.011	0.011	0.161	0.105	0.068
	0.13	0.10	0.659	-0.008	0.010	0.162	0.103	0.068
	0.13	0.08	0.606	-0.007	0.010	0.166	0.101	0.066
	0.15	0.24	0.808	-0.004	0.015	0.127	0.092	0.057
	0.16	0.22	0.800	-0.001	0.012	0.145	0.095	0.060
	0.17	0.19	0.759	-0.006	0.012	0.157	0.103	0.065
	0.17	0.16	0.697	-0.007	0.012	0.157	0.098	0.069
	0.18	0.14	0.653	-0.007	0.013	0.168	0.101	0.070
	0.19	0.12	0.570	-0.020	0.019	0.182	0.140	0.078
	0.20	0.23	0.725	0.006	0.014	0.147	0.096	0.064
	0.21	0.21	0.663	-0.001	0.013	0.167	0.105	0.069
7.5	-0.21	0.21	0.609	-0.031	0.010	0.165	0.107	0.074
(Hole 14)	-0.20	0.23	0.669	-0.032	0.012	0.155	0.099	0.071
	-0.19	0.12	0.564	-0.020	0.021	0.173	0.120	0.073
	-0.18	0.14	0.665	-0.031	0.009	0.159	0.107	0.073
	-0.17	0.16	0.715	-0.030	0.011	0.152	0.098	0.071
	-0.17	0.19	0.759	-0.030	0.012	0.153	0.099	0.068
	-0.16	0.22	0.804	-0.033	0.011	0.136	0.093	0.063
	-0.15	0.24	0.807	-0.033	0.013	0.131	0.091	0.061
	-0.13	0.08	0.676	-0.028	0.004	0.160	0.106	0.068
	-0.13	0.10	0.763	-0.031	0.002	0.145	0.094	0.065
	-0.12	0.12	0.816	-0.033	0.001	0.133	0.087	0.062
	-0.12	0.14	0.849	-0.034	0.000	0.125	0.081	0.060
	-0.12	0.16	0.890	-0.035	0.001	0.113	0.074	0.056
	-0.11	0.19	0.912	-0.034	0.001	0.110	0.081	0.053
	-0.11	0.21	0.914	-0.036	0.003	0.108	0.081	0.051
	-0.10	0.24	0.876	-0.024	0.008	0.110	0.085	0.051
	-0.07	0.05	0.724	-0.025	0.002	0.157	0.102	0.064
	-0.06	0.07	0.787	-0.027	0.001	0.149	0.098	0.063
	-0.06	0.09	0.844	-0.032	-0.003	0.137	0.091	0.059
	-0.06	0.11	0.882	-0.030	-0.004	0.127	0.087	0.057
	-0.06	0.13	0.912	-0.031	-0.005	0.115	0.083	0.052
	-0.06	0.15	0.936	-0.034	-0.007	0.104	0.079	0.050
	-0.06	0.18	0.938	-0.034	-0.010	0.100	0.084	0.048
	-0.05	0.21	0.920	-0.032	-0.014	0.101	0.084	0.046
	-0.05	0.24	0.881	-0.024	-0.013	0.109	0.093	0.050
	0.00	0.03	0.668	-0.009	0.004	0.164	0.118	0.065
	0.00	0.05	0.740	-0.020	0.005	0.153	0.099	0.065

	0.00	0.07	0.805	-0.021	0.001	0.139	0.091	0.062
	0.00	0.09	0.842	-0.026	-0.001	0.132	0.086	0.060
	0.00	0.11	0.869	-0.026	-0.001	0.125	0.082	0.059
	0.00	0.13	0.899	-0.029	-0.006	0.111	0.078	0.056
	0.00	0.15	0.925	-0.029	-0.010	0.097	0.072	0.051
	0.00	0.18	0.921	-0.026	-0.019	0.099	0.081	0.049
	0.00	0.21	0.895	-0.023	-0.029	0.111	0.088	0.048
	0.00	0.24	0.857	-0.021	-0.030	0.118	0.096	0.047
	0.05	0.24	0.856	-0.017	-0.021	0.098	0.083	0.051
	0.05	0.21	0.890	-0.016	-0.019	0.089	0.074	0.051
	0.06	0.18	0.901	-0.016	-0.011	0.098	0.076	0.053
	0.06	0.15	0.882	-0.019	-0.003	0.109	0.074	0.057
	0.06	0.13	0.863	-0.018	-0.001	0.117	0.081	0.060
	0.06	0.11	0.825	-0.018	0.004	0.128	0.087	0.063
	0.06	0.09	0.791	-0.016	0.004	0.141	0.090	0.063
	0.06	0.07	0.749	-0.012	0.008	0.145	0.096	0.066
	0.07	0.05	0.674	-0.009	0.009	0.159	0.101	0.066
	0.10	0.24	0.828	-0.015	0.006	0.110	0.087	0.054
	0.11	0.21	0.862	-0.009	0.003	0.115	0.086	0.056
	0.11	0.19	0.844	-0.010	0.004	0.129	0.088	0.059
	0.12	0.16	0.813	-0.012	0.009	0.132	0.081	0.062
	0.12	0.14	0.778	-0.011	0.012	0.144	0.088	0.065
	0.12	0.12	0.752	-0.010	0.011	0.148	0.093	0.066
	0.13	0.10	0.708	-0.005	0.011	0.155	0.099	0.067
	0.13	0.08	0.659	-0.001	0.011	0.164	0.102	0.065
	0.15	0.24	0.785	-0.008	0.019	0.128	0.089	0.058
	0.16	0.22	0.793	-0.001	0.015	0.137	0.090	0.061
	0.17	0.19	0.756	-0.003	0.015	0.151	0.096	0.065
	0.17	0.16	0.711	-0.002	0.017	0.157	0.095	0.068
	0.18	0.14	0.652	-0.004	0.020	0.165	0.101	0.070
	0.19	0.12	0.591	-0.006	0.021	0.168	0.116	0.071
	0.20	0.23	0.684	0.001	0.019	0.154	0.094	0.066
	0.21	0.21	0.631	-0.001	0.015	0.162	0.102	0.070

Table I.7. Culvert Placed at an Embedment of 0.2*D* with a Discharge of 50 L/s

x (m)	y (m)	z (m)	$\bar{u}$ (m/s)	$\bar{v}$ (m/s)	$\bar{w}$ (m/s)	$RMS_{u'}$ (m/s)	$RMS_{v'}$ (m/s)	$RMS_{w'}$ (m/s)
0.5	-0.21	0.18	0.362	-0.045	0.028	0.089	0.065	0.060
(Hole 2)	-0.18	0.14	0.447	-0.044	0.017	0.108	0.071	0.067
	-0.18	0.16	0.473	-0.047	0.017	0.095	0.067	0.073
	-0.17	0.18	0.447	-0.039	0.006	0.095	0.071	0.067
	-0.13	0.07	0.499	-0.026	0.007	0.114	0.117	0.061
	-0.13	0.09	0.553	-0.037	-0.002	0.111	0.065	0.056
	-0.12	0.11	0.584	-0.023	0.001	0.089	0.067	0.056
	-0.12	0.13	0.601	-0.023	-0.005	0.082	0.063	0.063
	-0.12	0.15	0.592	-0.020	-0.010	0.084	0.065	0.068
	-0.11	0.17	0.573	-0.015	-0.014	0.090	0.070	0.063
	-0.11	0.19	0.537	-0.005	-0.008	0.106	0.075	0.064
	-0.07	0.05	0.620	-0.036	-0.017	0.070	0.053	0.038
	-0.07	0.07	0.641	-0.021	-0.020	0.081	0.056	0.037
	-0.06	0.11	0.688	-0.010	-0.024	0.050	0.040	0.033

	-0.06	0.13	0.702	-0.012	-0.026	0.039	0.038	0.032
	-0.06	0.15	0.702	-0.014	-0.026	0.036	0.038	0.033
	-0.06	0.17	0.690	-0.021	-0.024	0.039	0.044	0.032
	-0.05	0.19	0.684	-0.020	-0.017	0.038	0.045	0.031
	0.00	0.05	0.665	-0.031	-0.020	0.056	0.043	0.029
	0.00	0.09	0.710	-0.016	-0.026	0.035	0.036	0.024
	0.00	0.11	0.714	-0.015	-0.024	0.032	0.034	0.026
	0.00	0.13	0.715	-0.018	-0.025	0.029	0.033	0.026
	0.00	0.15	0.712	-0.018	-0.023	0.029	0.033	0.028
	0.00	0.17	0.698	-0.022	-0.019	0.031	0.035	0.028
	0.00	0.19	0.690	-0.021	-0.014	0.032	0.038	0.026
	0.05	0.19	0.665	-0.018	-0.016	0.052	0.053	0.037
	0.06	0.17	0.678	-0.014	-0.026	0.044	0.049	0.035
	0.06	0.15	0.699	-0.015	-0.025	0.040	0.044	0.034
	0.06	0.13	0.707	-0.012	-0.018	0.036	0.039	0.034
	0.06	0.11	0.709	-0.013	-0.014	0.038	0.039	0.032
	0.07	0.07	0.647	-0.013	-0.008	0.085	0.052	0.031
	0.07	0.05	0.571	-0.017	-0.001	0.094	0.058	0.042
	0.11	0.19	0.485	-0.026	-0.007	0.115	0.079	0.067
	0.11	0.17	0.536	-0.014	-0.011	0.102	0.072	0.066
	0.12	0.15	0.585	-0.005	-0.015	0.078	0.063	0.057
	0.12	0.13	0.620	0.003	-0.011	0.065	0.058	0.055
	0.12	0.11	0.641	0.011	-0.003	0.065	0.058	0.049
	0.13	0.09	0.615	0.018	-0.009	0.084	0.056	0.038
	0.13	0.07	0.577	0.007	0.002	0.132	0.065	0.046
	0.17	0.18	0.446	-0.001	0.017	0.094	0.075	0.073
	0.18	0.16	0.482	0.025	0.004	0.097	0.071	0.070
	0.18	0.14	0.528	0.039	0.018	0.096	0.062	0.067
	0.21	0.18	0.393	0.034	0.034	0.093	0.065	0.066
1.5	-0.21	0.17	0.386	-0.055	0.020	0.088	0.061	0.057
(Hole 5)	-0.19	0.12	0.478	-0.059	0.008	0.100	0.069	0.057
	-0.18	0.14	0.438	-0.046	0.005	0.109	0.063	0.055
	-0.18	0.16	0.448	-0.032	0.013	0.092	0.074	0.059
	-0.17	0.18	0.436	-0.032	0.016	0.090	0.068	0.067
	-0.13	0.07	0.560	-0.046	0.006	0.105	0.063	0.053
	-0.13	0.09	0.594	-0.051	-0.001	0.097	0.059	0.051
	-0.12	0.11	0.596	-0.042	0.003	0.086	0.067	0.053
	-0.12	0.13	0.594	-0.042	0.004	0.077	0.057	0.055
	-0.12	0.15	0.574	-0.039	0.000	0.080	0.059	0.058
	-0.11	0.17	0.508	-0.025	-0.006	0.099	0.068	0.067
	-0.11	0.19	0.451	-0.006	-0.005	0.099	0.070	0.066
	-0.07	0.05	0.614	-0.032	-0.003	0.108	0.056	0.043
	-0.06	0.08	0.676	-0.040	-0.004	0.062	0.047	0.039
	-0.06	0.11	0.673	-0.037	-0.006	0.060	0.047	0.043
	-0.06	0.13	0.651	-0.034	-0.009	0.070	0.052	0.047
	-0.06	0.15	0.612	-0.028	-0.013	0.082	0.058	0.051
	-0.06	0.17	0.560	-0.017	-0.016	0.095	0.069	0.058
	-0.05	0.19	0.528	-0.013	-0.015	0.097	0.073	0.059
	0.00	0.03	0.547	-0.019	0.003	0.116	0.064	0.048
	0.00	0.05	0.627	-0.020	-0.001	0.101	0.055	0.043
	0.00	0.07	0.642	-0.031	0.002	0.078	0.066	0.040
	0.00	0.09	0.688	-0.021	-0.005	0.057	0.043	0.039

	0.00	0.11	0.687	-0.019	-0.007	0.057	0.045	0.039
	0.00	0.13	0.661	-0.019	-0.012	0.070	0.051	0.044
	0.00	0.15	0.616	-0.017	-0.017	0.085	0.058	0.049
	0.00	0.17	0.612	-0.020	-0.021	0.090	0.064	0.052
	0.00	0.19	0.559	-0.021	-0.021	0.095	0.071	0.053
	0.05	0.19	0.528	-0.023	-0.012	0.094	0.072	0.060
	0.06	0.17	0.567	-0.015	-0.013	0.092	0.068	0.060
	0.06	0.15	0.625	-0.010	-0.012	0.082	0.059	0.054
	0.06	0.13	0.656	-0.006	-0.008	0.072	0.054	0.052
	0.06	0.11	0.669	-0.005	-0.003	0.068	0.051	0.049
	0.06	0.09	0.667	-0.016	-0.003	0.076	0.065	0.046
	0.07	0.07	0.611	-0.010	-0.002	0.102	0.059	0.046
	0.07	0.05	0.571	-0.012	0.003	0.107	0.066	0.051
	0.11	0.19	0.526	-0.012	0.015	0.087	0.069	0.064
	0.11	0.17	0.571	0.003	0.015	0.083	0.066	0.063
	0.12	0.15	0.584	0.005	0.009	0.081	0.060	0.061
	0.12	0.13	0.605	0.008	0.010	0.080	0.070	0.057
	0.12	0.11	0.609	0.006	0.009	0.085	0.066	0.053
	0.13	0.09	0.587	0.010	0.008	0.098	0.061	0.051
	0.13	0.07	0.548	0.012	0.001	0.129	0.130	0.061
	0.17	0.18	0.498	0.005	0.035	0.086	0.067	0.060
	0.18	0.16	0.499	0.022	0.018	0.102	0.062	0.055
	0.18	0.14	0.492	0.015	0.020	0.099	0.067	0.053
	0.21	0.17	0.375	0.001	0.026	0.123	0.129	0.075
4.0	-0.20	0.18	0.383	-0.026	0.007	0.084	0.054	0.041
(Hole 8)	-0.19	0.12	0.404	-0.028	0.000	0.091	0.057	0.043
	-0.18	0.14	0.458	-0.022	0.002	0.083	0.058	0.042
	-0.17	0.16	0.461	-0.019	0.006	0.082	0.053	0.041
	-0.17	0.19	0.470	-0.024	0.010	0.063	0.045	0.038
	-0.13	0.08	0.448	-0.022	0.001	0.091	0.055	0.041
	-0.13	0.10	0.469	-0.032	-0.001	0.098	0.056	0.039
	-0.12	0.12	0.513	-0.028	0.001	0.076	0.057	0.039
	-0.12	0.14	0.537	-0.028	0.000	0.068	0.065	0.036
	-0.12	0.16	0.541	-0.033	-0.002	0.054	0.040	0.036
	-0.11	0.17	0.529	-0.031	0.001	0.051	0.039	0.036
	-0.11	0.20	0.519	-0.026	-0.001	0.050	0.039	0.037
	-0.07	0.05	0.468	-0.013	0.001	0.089	0.059	0.041
	-0.06	0.09	0.543	-0.019	0.001	0.069	0.054	0.037
	-0.06	0.11	0.563	-0.024	-0.002	0.052	0.038	0.034
	-0.06	0.13	0.568	-0.026	-0.004	0.048	0.037	0.035
	-0.06	0.15	0.562	-0.027	-0.007	0.046	0.036	0.034
	-0.06	0.17	0.540	-0.026	-0.012	0.046	0.036	0.035
	-0.05	0.20	0.528	-0.021	-0.013	0.050	0.039	0.035
	0.00	0.03	0.430	-0.008	0.004	0.107	0.056	0.042
	0.00	0.05	0.480	-0.020	0.001	0.099	0.054	0.042
	0.00	0.09	0.563	-0.018	0.003	0.060	0.041	0.035
	0.00	0.11	0.575	-0.019	0.000	0.051	0.039	0.034
	0.00	0.13	0.574	-0.019	-0.001	0.048	0.037	0.034
	0.00	0.15	0.569	-0.019	-0.005	0.047	0.037	0.034
	0.00	0.18	0.552	-0.021	-0.012	0.047	0.037	0.033
	0.00	0.20	0.537	-0.020	-0.017	0.049	0.039	0.032
	0.05	0.20	0.549	-0.017	-0.005	0.049	0.037	0.033

	0.06	0.17	0.562	-0.016	0.000	0.047	0.036	0.032
	0.06	0.15	0.574	-0.013	0.004	0.047	0.037	0.033
	0.06	0.13	0.570	-0.012	0.006	0.052	0.039	0.034
	0.06	0.11	0.553	-0.011	0.007	0.063	0.042	0.035
	0.06	0.09	0.533	-0.022	0.008	0.080	0.072	0.038
	0.06	0.07	0.495	-0.014	0.005	0.087	0.061	0.038
	0.07	0.05	0.450	-0.007	0.005	0.093	0.057	0.041
	0.11	0.20	0.547	-0.012	0.011	0.051	0.038	0.033
	0.11	0.17	0.552	-0.008	0.012	0.054	0.038	0.034
	0.12	0.16	0.545	-0.009	0.012	0.062	0.041	0.036
	0.12	0.14	0.531	-0.003	0.008	0.071	0.054	0.037
	0.12	0.12	0.486	-0.013	0.011	0.090	0.058	0.040
	0.13	0.10	0.455	-0.001	0.011	0.095	0.058	0.041
	0.13	0.08	0.416	-0.003	0.008	0.092	0.056	0.041
	0.16	0.20	0.480	-0.005	0.017	0.071	0.047	0.041
	0.17	0.16	0.427	-0.010	0.018	0.095	0.058	0.042
	0.18	0.14	0.396	0.001	0.014	0.093	0.060	0.044
	0.20	0.18	0.369	0.001	0.014	0.092	0.060	0.043
6.5	-0.21	0.17	0.368	-0.022	0.008	0.084	0.052	0.041
(Hole 11)	-0.20	0.21	0.390	-0.018	0.011	0.077	0.050	0.041
	-0.19	0.11	0.367	-0.024	0.000	0.140	0.057	0.042
	-0.18	0.13	0.408	-0.030	0.004	0.080	0.060	0.040
	-0.18	0.15	0.445	-0.030	0.008	0.080	0.053	0.039
	-0.17	0.18	0.446	-0.019	0.011	0.067	0.047	0.038
	-0.16	0.20	0.454	-0.023	0.009	0.063	0.040	0.036
	-0.13	0.07	0.402	-0.018	0.002	0.081	0.051	0.038
	-0.13	0.09	0.444	-0.030	0.003	0.083	0.059	0.036
	-0.12	0.11	0.485	-0.019	0.001	0.076	0.068	0.038
	-0.12	0.13	0.508	-0.023	0.001	0.058	0.040	0.032
	-0.12	0.15	0.517	-0.029	0.001	0.052	0.039	0.032
	-0.11	0.18	0.516	-0.028	0.004	0.047	0.035	0.032
	-0.11	0.21	0.499	-0.022	0.004	0.050	0.035	0.033
	-0.07	0.04	0.423	-0.015	0.005	0.082	0.051	0.038
	-0.07	0.06	0.460	-0.027	0.004	0.085	0.067	0.034
	-0.06	0.08	0.503	-0.016	0.003	0.069	0.049	0.034
	-0.06	0.10	0.530	-0.021	0.001	0.054	0.035	0.030
	-0.06	0.12	0.548	-0.022	-0.001	0.044	0.032	0.029
	-0.06	0.14	0.549	-0.024	-0.002	0.040	0.030	0.028
	-0.06	0.17	0.534	-0.024	-0.005	0.042	0.032	0.029
	-0.05	0.20	0.513	-0.019	-0.008	0.045	0.034	0.030
	0.00	0.02	0.395	-0.008	0.005	0.092	0.052	0.037
	0.00	0.04	0.438	-0.011	0.007	0.079	0.058	0.037
	0.00	0.08	0.520	-0.013	0.003	0.061	0.038	0.032
	0.00	0.10	0.541	-0.014	0.003	0.051	0.034	0.029
	0.00	0.12	0.557	-0.015	0.001	0.042	0.031	0.028
	0.00	0.14	0.557	-0.015	-0.001	0.039	0.029	0.027
	0.00	0.18	0.545	-0.018	-0.009	0.042	0.031	0.027
	0.00	0.21	0.515	-0.015	-0.015	0.046	0.035	0.028
	0.05	0.20	0.531	-0.012	-0.003	0.044	0.033	0.029
	0.06	0.17	0.550	-0.011	0.001	0.041	0.031	0.028
	0.06	0.14	0.541	-0.010	0.005	0.045	0.032	0.029
	0.06	0.12	0.530	-0.011	0.007	0.053	0.035	0.031

	0.06	0.10	0.511	-0.010	0.008	0.061	0.039	0.033
	0.06	0.08	0.487	-0.014	0.006	0.074	0.058	0.034
	0.07	0.06	0.454	-0.010	0.007	0.080	0.063	0.035
	0.07	0.04	0.419	-0.006	0.007	0.080	0.050	0.037
	0.11	0.21	0.515	-0.007	0.008	0.049	0.035	0.032
	0.11	0.18	0.523	-0.007	0.009	0.050	0.036	0.032
	0.12	0.15	0.493	-0.007	0.010	0.061	0.039	0.034
	0.12	0.13	0.475	-0.006	0.009	0.069	0.043	0.035
	0.13	0.09	0.407	-0.006	0.012	0.088	0.072	0.038
	0.13	0.07	0.378	0.003	0.008	0.086	0.052	0.039
	0.16	0.20	0.451	-0.002	0.014	0.067	0.042	0.038
	0.17	0.18	0.439	-0.007	0.014	0.077	0.053	0.040
	0.18	0.15	0.385	-0.015	0.013	0.090	0.052	0.041
	0.18	0.13	0.380	0.006	0.013	0.082	0.053	0.039
	0.19	0.11	0.349	0.003	0.008	0.092	0.069	0.045
	0.20	0.21	0.391	-0.002	0.017	0.079	0.050	0.041
	0.21	0.17	0.342	0.000	0.016	0.084	0.055	0.042
7.5	-0.21	0.18	0.352	-0.019	0.009	0.090	0.049	0.040
(Hole 14)	-0.20	0.20	0.390	-0.021	0.011	0.075	0.047	0.040
	-0.19	0.11	0.370	-0.032	0.006	0.087	0.063	0.040
	-0.18	0.13	0.407	-0.024	0.008	0.094	0.051	0.039
	-0.18	0.15	0.416	-0.023	0.011	0.085	0.060	0.041
	-0.17	0.18	0.440	-0.010	0.014	0.069	0.045	0.038
	-0.16	0.20	0.446	-0.018	0.012	0.064	0.040	0.036
	-0.13	0.07	0.424	-0.019	0.008	0.082	0.053	0.037
	-0.13	0.09	0.458	-0.016	0.009	0.077	0.055	0.034
	-0.12	0.11	0.490	-0.016	0.007	0.073	0.056	0.034
	-0.12	0.13	0.515	-0.025	0.005	0.055	0.037	0.032
	-0.12	0.15	0.523	-0.026	0.005	0.049	0.035	0.031
	-0.11	0.18	0.518	-0.022	0.008	0.047	0.034	0.030
	-0.11	0.21	0.504	-0.016	0.008	0.048	0.034	0.031
	-0.07	0.04	0.451	-0.016	0.007	0.081	0.053	0.037
	-0.07	0.06	0.474	-0.015	0.006	0.081	0.062	0.038
	-0.06	0.08	0.518	-0.021	0.006	0.059	0.039	0.032
	-0.06	0.10	0.544	-0.023	0.004	0.047	0.033	0.028
	-0.06	0.12	0.554	-0.024	0.002	0.040	0.031	0.027
	-0.06	0.14	0.553	-0.025	0.001	0.038	0.030	0.027
	-0.06	0.17	0.539	-0.021	0.000	0.041	0.031	0.027
	-0.05	0.20	0.516	-0.013	-0.003	0.046	0.033	0.029
	0.00	0.02	0.426	-0.013	0.008	0.081	0.050	0.037
	0.00	0.04	0.460	-0.012	0.010	0.081	0.066	0.035
	0.00	0.06	0.502	-0.022	0.008	0.067	0.050	0.029
	0.00	0.08	0.538	-0.015	0.005	0.055	0.035	0.030
	0.00	0.10	0.556	-0.017	0.003	0.043	0.031	0.027
	0.00	0.12	0.562	-0.018	0.000	0.038	0.029	0.026
	0.00	0.14	0.560	-0.017	-0.003	0.037	0.028	0.026
	0.00	0.18	0.534	-0.014	-0.011	0.040	0.031	0.026
	0.00	0.21	0.509	-0.011	-0.015	0.044	0.035	0.026
	0.05	0.20	0.510	-0.012	-0.009	0.044	0.034	0.028
	0.06	0.17	0.537	-0.008	-0.005	0.039	0.030	0.026
	0.06	0.14	0.551	-0.009	0.001	0.038	0.028	0.026
	0.06	0.12	0.550	-0.009	0.005	0.041	0.030	0.027

	0.06	0.10	0.540	-0.010	0.006	0.049	0.033	0.029
	0.06	0.08	0.519	-0.008	0.008	0.057	0.038	0.031
	0.07	0.06	0.494	-0.009	0.007	0.075	0.061	0.033
	0.07	0.04	0.462	-0.010	0.008	0.078	0.056	0.035
	0.11	0.21	0.499	-0.007	0.006	0.048	0.034	0.032
	0.11	0.18	0.517	-0.002	0.006	0.046	0.034	0.030
	0.12	0.15	0.520	-0.003	0.009	0.051	0.034	0.030
	0.12	0.13	0.507	-0.004	0.009	0.060	0.037	0.032
	0.12	0.11	0.485	0.002	0.009	0.070	0.054	0.035
	0.13	0.09	0.451	-0.005	0.010	0.088	0.049	0.037
	0.13	0.07	0.410	0.005	0.012	0.083	0.060	0.038
	0.16	0.20	0.455	-0.002	0.014	0.060	0.038	0.034
	0.17	0.18	0.451	-0.004	0.017	0.066	0.047	0.036
	0.18	0.15	0.425	-0.003	0.018	0.082	0.052	0.038
	0.18	0.13	0.407	0.001	0.013	0.087	0.050	0.038
	0.19	0.11	0.374	0.009	0.010	0.093	0.057	0.040
	0.20	0.20	0.382	-0.002	0.016	0.078	0.055	0.042
	0.21	0.18	0.355	-0.004	0.016	0.091	0.050	0.040

Table I.8. Culvert Placed at an Embedment of 0.2*D* with a Discharge of 70 L/s

x (m)	y (m)	z (m)	$\bar{u}$ (m/s)	$\bar{v}$ (m/s)	$\bar{w}$ (m/s)	$RMS_{u'}$ (m/s)	$RMS_{v'}$ (m/s)	$RMS_{w'}$ (m/s)
0.5	-0.21	0.20	0.446	-0.023	0.020	0.116	0.087	0.076
(Hole 2)	-0.21	0.21	0.445	-0.010	0.021	0.128	0.086	0.075
	-0.18	0.13	0.576	-0.038	-0.006	0.102	0.076	0.062
	-0.18	0.15	0.585	-0.017	-0.015	0.102	0.072	0.062
	-0.17	0.18	0.608	-0.003	-0.019	0.110	0.076	0.063
	-0.16	0.21	0.605	0.002	-0.015	0.144	0.096	0.065
	-0.13	0.07	0.579	-0.031	-0.001	0.132	0.114	0.052
	-0.13	0.09	0.619	-0.022	-0.006	0.103	0.076	0.045
	-0.12	0.11	0.662	-0.010	-0.014	0.102	0.074	0.043
	-0.12	0.13	0.729	-0.007	-0.024	0.087	0.073	0.038
	-0.12	0.15	0.737	-0.003	-0.029	0.076	0.069	0.036
	-0.11	0.18	0.743	-0.003	-0.028	0.081	0.076	0.036
	-0.11	0.20	0.737	-0.009	-0.019	0.077	0.071	0.035
	-0.07	0.04	0.644	-0.029	-0.017	0.084	0.066	0.038
	-0.07	0.06	0.701	-0.013	-0.018	0.076	0.062	0.035
	-0.06	0.08	0.736	-0.009	-0.016	0.066	0.059	0.030
	-0.06	0.10	0.748	-0.011	-0.013	0.054	0.053	0.028
	-0.06	0.12	0.754	-0.010	-0.016	0.047	0.049	0.028
	-0.06	0.14	0.754	-0.014	-0.011	0.042	0.045	0.027
	-0.06	0.16	0.768	-0.017	-0.019	0.070	0.068	0.033
	-0.05	0.19	0.762	-0.020	-0.015	0.070	0.070	0.034
	-0.05	0.21	0.752	-0.021	-0.009	0.065	0.067	0.030
	0.00	0.04	0.661	-0.025	-0.002	0.095	0.081	0.037
	0.00	0.06	0.694	-0.020	-0.003	0.086	0.078	0.033
	0.00	0.08	0.734	-0.021	-0.001	0.080	0.075	0.030
	0.00	0.10	0.749	-0.017	0.000	0.069	0.067	0.028
	0.00	0.12	0.750	-0.022	0.004	0.089	0.084	0.034
	0.00	0.14	0.760	-0.022	0.001	0.090	0.085	0.035
	0.00	0.17	0.756	-0.025	-0.001	0.056	0.056	0.033

	0.00	0.19	0.749	-0.023	0.000	0.054	0.054	0.034
	0.00	0.21	0.742	-0.024	0.003	0.055	0.054	0.030
	0.05	0.21	0.737	-0.020	0.008	0.069	0.067	0.033
	0.05	0.19	0.738	-0.021	0.001	0.067	0.065	0.032
	0.06	0.16	0.740	-0.029	0.000	0.070	0.067	0.033
	0.06	0.14	0.765	-0.031	-0.001	0.051	0.051	0.031
	0.06	0.12	0.748	-0.033	0.000	0.055	0.055	0.029
	0.06	0.10	0.741	-0.031	0.000	0.061	0.058	0.028
	0.06	0.08	0.729	-0.030	-0.001	0.069	0.062	0.030
	0.07	0.06	0.705	-0.029	-0.002	0.078	0.065	0.033
	0.07	0.04	0.636	-0.023	-0.002	0.086	0.068	0.037
	0.11	0.20	0.745	-0.025	-0.001	0.083	0.076	0.035
	0.11	0.18	0.750	-0.033	-0.006	0.088	0.079	0.038
	0.12	0.15	0.740	-0.036	-0.004	0.078	0.069	0.036
	0.12	0.13	0.730	-0.032	-0.005	0.093	0.075	0.037
	0.12	0.11	0.681	-0.027	-0.001	0.094	0.064	0.040
	0.13	0.09	0.619	-0.023	0.003	0.099	0.067	0.046
	0.16	0.21	0.710	-0.029	-0.001	0.073	0.055	0.041
	0.17	0.18	0.661	-0.034	-0.001	0.104	0.070	0.052
	0.18	0.15	0.611	-0.022	0.001	0.117	0.076	0.060
	0.18	0.13	0.599	-0.012	0.008	0.122	0.078	0.059
	0.21	0.21	0.578	-0.021	0.013	0.126	0.072	0.059
	0.21	0.20	0.511	-0.018	0.018	0.126	0.082	0.067
1.5	-0.21	0.20	0.464	-0.039	0.016	0.120	0.092	0.064
(Hole 5)	-0.21	0.21	0.466	-0.036	0.017	0.121	0.092	0.065
	-0.19	0.11	0.525	-0.032	0.009	0.123	0.105	0.064
	-0.18	0.13	0.582	-0.043	0.006	0.116	0.075	0.057
	-0.18	0.15	0.623	-0.047	0.005	0.108	0.073	0.059
	-0.17	0.18	0.594	-0.045	0.004	0.112	0.088	0.060
	-0.16	0.21	0.545	-0.030	0.008	0.115	0.093	0.064
	-0.13	0.07	0.604	-0.034	0.002	0.114	0.071	0.048
	-0.13	0.09	0.641	-0.028	0.000	0.125	0.088	0.048
	-0.12	0.11	0.658	-0.028	-0.003	0.114	0.085	0.046
	-0.12	0.13	0.676	-0.030	-0.005	0.101	0.078	0.045
	-0.12	0.15	0.686	-0.029	-0.010	0.097	0.076	0.046
	-0.11	0.18	0.675	-0.037	-0.016	0.094	0.082	0.045
	-0.11	0.20	0.633	-0.029	-0.013	0.109	0.087	0.049
	-0.07	0.04	0.649	-0.025	0.000	0.117	0.084	0.044
	-0.07	0.06	0.695	-0.027	-0.001	0.100	0.075	0.038
	-0.06	0.08	0.719	-0.025	-0.002	0.084	0.069	0.034
	-0.06	0.10	0.743	-0.028	-0.003	0.078	0.067	0.032
	-0.06	0.12	0.766	-0.032	-0.004	0.072	0.063	0.032
	-0.06	0.14	0.767	-0.035	-0.008	0.064	0.058	0.033
	-0.06	0.16	0.753	-0.034	-0.009	0.056	0.053	0.032
	-0.05	0.19	0.752	-0.034	-0.014	0.078	0.073	0.037
	-0.05	0.21	0.731	-0.028	-0.011	0.105	0.088	0.043
	0.00	0.02	0.580	-0.017	0.001	0.146	0.088	0.048
	0.00	0.04	0.652	-0.022	0.005	0.112	0.079	0.043
	0.00	0.06	0.703	-0.022	0.004	0.092	0.071	0.037
	0.00	0.08	0.728	-0.024	0.003	0.078	0.064	0.032
	0.00	0.10	0.736	-0.026	0.005	0.070	0.062	0.029
	0.00	0.12	0.772	-0.030	0.005	0.070	0.063	0.030

	0.00	0.14	0.773	-0.031	0.001	0.069	0.063	0.031
	0.00	0.17	0.774	-0.033	-0.006	0.075	0.067	0.032
	0.00	0.19	0.762	-0.030	-0.009	0.079	0.068	0.032
	0.00	0.21	0.760	-0.025	-0.012	0.090	0.078	0.036
	0.05	0.21	0.750	-0.022	-0.002	0.063	0.058	0.032
	0.05	0.19	0.760	-0.024	-0.006	0.067	0.061	0.033
	0.06	0.16	0.769	-0.025	-0.004	0.073	0.064	0.033
	0.06	0.14	0.768	-0.027	0.002	0.061	0.052	0.032
	0.06	0.12	0.769	-0.026	0.005	0.067	0.058	0.033
	0.06	0.10	0.717	-0.025	0.005	0.086	0.063	0.036
	0.06	0.08	0.683	-0.021	0.005	0.095	0.067	0.040
	0.07	0.06	0.641	-0.021	0.005	0.110	0.075	0.046
	0.07	0.04	0.578	-0.015	0.008	0.127	0.084	0.049
	0.11	0.20	0.684	-0.013	-0.007	0.094	0.080	0.042
	0.11	0.18	0.691	-0.015	-0.004	0.097	0.081	0.041
	0.12	0.15	0.731	-0.015	0.003	0.098	0.075	0.043
	0.12	0.13	0.699	-0.014	0.006	0.108	0.078	0.046
	0.12	0.11	0.671	-0.014	0.008	0.125	0.083	0.048
	0.13	0.09	0.608	-0.012	0.008	0.138	0.090	0.053
	0.13	0.07	0.514	-0.025	0.015	0.147	0.124	0.061
	0.16	0.21	0.593	-0.003	0.011	0.114	0.086	0.055
	0.17	0.18	0.595	-0.002	0.012	0.115	0.088	0.057
	0.18	0.15	0.588	-0.007	0.012	0.119	0.074	0.057
	0.18	0.13	0.558	-0.006	0.013	0.132	0.102	0.062
	0.21	0.21	0.473	0.004	0.018	0.129	0.089	0.059
	0.21	0.20	0.466	0.000	0.017	0.135	0.099	0.063
4.0	-0.21	0.20	0.487	-0.029	0.005	0.131	0.090	0.059
(Hole 8)	-0.20	0.22	0.518	-0.031	0.008	0.119	0.080	0.056
	-0.19	0.11	0.454	-0.027	0.005	0.153	0.131	0.067
	-0.18	0.13	0.514	-0.028	0.004	0.132	0.092	0.058
	-0.18	0.15	0.549	-0.030	0.005	0.122	0.084	0.056
	-0.17	0.18	0.585	-0.026	0.007	0.119	0.086	0.054
	-0.16	0.20	0.604	-0.035	0.008	0.114	0.084	0.054
	-0.16	0.23	0.602	-0.032	0.011	0.107	0.079	0.052
	-0.13	0.07	0.513	-0.028	0.000	0.141	0.091	0.056
	-0.13	0.09	0.573	-0.029	0.002	0.140	0.083	0.053
	-0.12	0.11	0.617	-0.037	0.002	0.128	0.095	0.051
	-0.12	0.13	0.644	-0.035	0.005	0.120	0.088	0.049
	-0.12	0.15	0.676	-0.036	0.005	0.113	0.084	0.050
	-0.11	0.17	0.675	-0.037	0.005	0.092	0.068	0.045
	-0.11	0.20	0.673	-0.038	0.005	0.085	0.065	0.045
	-0.10	0.23	0.646	-0.033	0.003	0.084	0.063	0.045
	-0.07	0.04	0.522	-0.021	0.003	0.128	0.089	0.054
	-0.07	0.06	0.595	-0.024	0.003	0.120	0.084	0.052
	-0.06	0.08	0.635	-0.029	0.004	0.113	0.077	0.049
	-0.06	0.10	0.667	-0.029	0.004	0.112	0.081	0.048
	-0.06	0.12	0.704	-0.033	0.004	0.101	0.076	0.045
	-0.06	0.14	0.717	-0.037	0.003	0.090	0.071	0.043
	-0.06	0.17	0.701	-0.033	-0.003	0.110	0.087	0.044
	-0.05	0.20	0.685	-0.029	-0.003	0.108	0.090	0.044
	-0.05	0.23	0.647	-0.023	-0.005	0.109	0.089	0.045
	0.00	0.02	0.485	-0.017	0.004	0.149	0.098	0.054

	0.00	0.04	0.564	-0.019	0.004	0.135	0.096	0.052
	0.00	0.06	0.594	-0.022	0.006	0.131	0.091	0.052
	0.00	0.08	0.638	-0.024	0.004	0.117	0.084	0.049
	0.00	0.10	0.669	-0.025	0.004	0.112	0.082	0.047
	0.00	0.12	0.711	-0.026	0.003	0.105	0.079	0.044
	0.00	0.14	0.717	-0.027	0.002	0.097	0.079	0.043
	0.00	0.17	0.691	-0.029	-0.005	0.119	0.077	0.043
	0.00	0.21	0.670	-0.025	-0.013	0.116	0.084	0.043
	0.00	0.23	0.634	-0.016	-0.015	0.100	0.081	0.043
	0.05	0.23	0.637	-0.010	-0.015	0.111	0.095	0.045
	0.05	0.20	0.676	-0.018	-0.008	0.074	0.053	0.041
	0.06	0.17	0.669	-0.017	0.001	0.075	0.053	0.039
	0.06	0.14	0.697	-0.018	0.002	0.101	0.079	0.045
	0.06	0.12	0.671	-0.017	0.004	0.107	0.080	0.047
	0.06	0.10	0.657	-0.019	0.004	0.117	0.086	0.049
	0.06	0.08	0.624	-0.020	0.006	0.131	0.095	0.052
	0.07	0.06	0.572	-0.018	0.007	0.139	0.097	0.055
	0.07	0.04	0.502	-0.016	0.006	0.141	0.098	0.056
	0.10	0.23	0.641	-0.009	0.001	0.092	0.071	0.047
	0.11	0.20	0.656	-0.010	0.002	0.095	0.072	0.048
	0.11	0.17	0.658	-0.010	0.005	0.103	0.075	0.048
	0.12	0.15	0.645	-0.012	0.007	0.116	0.086	0.051
	0.12	0.13	0.632	-0.012	0.007	0.112	0.077	0.050
	0.12	0.11	0.599	-0.013	0.006	0.129	0.085	0.053
	0.13	0.09	0.537	-0.016	0.005	0.133	0.088	0.055
	0.13	0.07	0.450	-0.004	0.002	0.149	0.112	0.056
	0.16	0.23	0.609	-0.004	0.012	0.095	0.064	0.049
	0.16	0.20	0.601	-0.005	0.012	0.108	0.069	0.050
	0.17	0.18	0.579	-0.005	0.013	0.120	0.077	0.054
	0.18	0.15	0.543	-0.003	0.011	0.136	0.093	0.058
	0.18	0.13	0.491	-0.006	0.012	0.148	0.107	0.064
	0.20	0.22	0.514	0.002	0.020	0.133	0.085	0.058
	0.21	0.20	0.478	-0.016	0.023	0.145	0.109	0.067
6.5	-0.21	0.20	0.425	-0.027	0.009	0.117	0.084	0.055
(Hole 11)	-0.20	0.23	0.465	-0.024	0.011	0.108	0.079	0.053
	-0.19	0.11	0.405	-0.013	0.014	0.163	0.093	0.059
	-0.18	0.13	0.468	-0.031	0.010	0.118	0.080	0.052
	-0.18	0.15	0.504	-0.029	0.010	0.112	0.076	0.052
	-0.17	0.18	0.524	-0.024	0.010	0.107	0.081	0.050
	-0.16	0.20	0.540	-0.022	0.010	0.104	0.080	0.048
	-0.16	0.23	0.547	-0.028	0.010	0.098	0.076	0.046
	-0.13	0.07	0.496	-0.022	0.003	0.128	0.085	0.050
	-0.13	0.09	0.536	-0.032	0.007	0.132	0.088	0.050
	-0.12	0.11	0.574	-0.029	0.007	0.116	0.083	0.049
	-0.12	0.13	0.598	-0.029	0.006	0.107	0.078	0.047
	-0.12	0.15	0.630	-0.031	0.006	0.115	0.090	0.047
	-0.11	0.17	0.596	-0.026	0.006	0.092	0.074	0.042
	-0.11	0.20	0.613	-0.028	0.005	0.086	0.073	0.041
	-0.10	0.23	0.594	-0.024	0.006	0.087	0.071	0.040
	-0.07	0.04	0.505	-0.022	0.008	0.131	0.096	0.050
	-0.07	0.06	0.563	-0.024	0.009	0.126	0.094	0.049
	-0.06	0.08	0.592	-0.024	0.009	0.123	0.091	0.047

	-0.06	0.10	0.624	-0.027	0.008	0.111	0.088	0.045
	-0.06	0.12	0.644	-0.026	0.007	0.104	0.081	0.043
	-0.06	0.14	0.668	-0.029	0.005	0.094	0.074	0.040
	-0.06	0.17	0.623	-0.025	0.000	0.080	0.068	0.037
	-0.05	0.20	0.626	-0.026	-0.005	0.081	0.071	0.036
	-0.05	0.23	0.602	-0.021	-0.007	0.083	0.069	0.038
	0.00	0.02	0.461	-0.020	0.008	0.144	0.107	0.049
	0.00	0.04	0.530	-0.021	0.007	0.112	0.081	0.048
	0.00	0.06	0.568	-0.020	0.007	0.109	0.074	0.047
	0.00	0.08	0.607	-0.022	0.008	0.115	0.086	0.046
	0.00	0.10	0.634	-0.021	0.007	0.106	0.081	0.043
	0.00	0.12	0.656	-0.022	0.005	0.103	0.083	0.042
	0.00	0.14	0.682	-0.022	0.001	0.094	0.080	0.039
	0.00	0.17	0.641	-0.023	-0.004	0.081	0.066	0.035
	0.00	0.21	0.670	-0.022	-0.014	0.092	0.069	0.038
	0.00	0.24	0.629	-0.018	-0.021	0.079	0.061	0.038
	0.05	0.23	0.576	-0.009	-0.015	0.081	0.068	0.036
	0.05	0.20	0.600	-0.010	-0.009	0.079	0.068	0.035
	0.06	0.17	0.627	-0.011	-0.001	0.080	0.069	0.036
	0.06	0.14	0.672	-0.017	0.005	0.077	0.058	0.039
	0.06	0.12	0.659	-0.017	0.006	0.089	0.065	0.041
	0.06	0.10	0.644	-0.015	0.007	0.099	0.071	0.043
	0.06	0.08	0.602	-0.015	0.008	0.113	0.080	0.047
	0.07	0.06	0.576	-0.015	0.009	0.121	0.086	0.050
	0.07	0.04	0.510	-0.014	0.009	0.123	0.089	0.050
	0.10	0.23	0.578	-0.005	-0.001	0.084	0.071	0.040
	0.11	0.20	0.602	-0.004	0.003	0.085	0.071	0.041
	0.11	0.17	0.610	-0.006	0.005	0.088	0.073	0.040
	0.12	0.15	0.614	-0.011	0.008	0.104	0.074	0.045
	0.12	0.13	0.599	-0.009	0.008	0.109	0.077	0.047
	0.12	0.11	0.573	-0.009	0.008	0.118	0.086	0.050
	0.13	0.09	0.533	-0.008	0.009	0.129	0.090	0.052
	0.13	0.07	0.489	-0.007	0.008	0.124	0.088	0.051
	0.16	0.23	0.548	-0.003	0.013	0.096	0.075	0.045
	0.16	0.20	0.530	0.006	0.011	0.101	0.077	0.046
	0.17	0.18	0.529	-0.003	0.012	0.106	0.078	0.048
	0.18	0.15	0.538	-0.007	0.013	0.114	0.075	0.053
	0.18	0.13	0.498	-0.002	0.012	0.122	0.082	0.054
	0.19	0.11	0.452	0.005	0.007	0.156	0.117	0.065
	0.20	0.23	0.482	0.003	0.016	0.108	0.079	0.051
	0.21	0.20	0.432	0.000	0.015	0.117	0.084	0.053
7.5	-0.21	0.20	0.431	-0.030	0.009	0.116	0.079	0.052
(Hole 14)	-0.20	0.23	0.465	-0.025	0.012	0.105	0.072	0.049
	-0.19	0.11	0.462	-0.025	0.010	0.120	0.094	0.052
	-0.18	0.13	0.482	-0.022	0.012	0.122	0.092	0.053
	-0.18	0.15	0.460	-0.019	0.008	0.125	0.099	0.050
	-0.17	0.18	0.531	-0.025	0.012	0.107	0.081	0.050
	-0.16	0.21	0.545	-0.023	0.012	0.101	0.077	0.048
	-0.15	0.24	0.546	-0.023	0.013	0.094	0.074	0.046
	-0.13	0.07	0.504	-0.023	0.007	0.117	0.090	0.047
	-0.13	0.09	0.533	-0.020	0.008	0.112	0.093	0.047
	-0.12	0.11	0.578	-0.022	0.008	0.114	0.090	0.045

-0.12	0.13	0.591	-0.021	0.007	0.104	0.086	0.044
-0.12	0.15	0.490	-0.019	0.009	0.122	0.095	0.047
-0.11	0.18	0.615	-0.026	0.006	0.089	0.073	0.041
-0.11	0.21	0.620	-0.026	0.007	0.084	0.071	0.039
-0.10	0.23	0.598	-0.020	0.006	0.084	0.069	0.039
-0.07	0.04	0.538	-0.020	0.009	0.119	0.091	0.046
-0.07	0.06	0.570	-0.021	0.008	0.111	0.090	0.043
-0.06	0.08	0.596	-0.024	0.007	0.106	0.086	0.041
-0.06	0.10	0.629	-0.023	0.004	0.098	0.085	0.039
-0.06	0.12	0.642	-0.023	0.003	0.094	0.083	0.038
-0.06	0.14	0.467	-0.017	0.008	0.123	0.096	0.047
-0.06	0.17	0.646	-0.028	0.001	0.071	0.061	0.034
-0.05	0.20	0.635	-0.027	-0.006	0.073	0.060	0.034
-0.05	0.24	0.612	-0.021	-0.008	0.072	0.057	0.035
0.00	0.04	0.519	-0.017	0.009	0.118	0.090	0.045
0.00	0.06	0.568	-0.016	0.007	0.112	0.089	0.043
0.00	0.08	0.596	-0.019	0.008	0.106	0.084	0.041
0.00	0.10	0.618	-0.021	0.007	0.097	0.081	0.039
0.00	0.12	0.647	-0.019	0.004	0.092	0.080	0.038
0.00	0.14	0.658	-0.021	0.001	0.088	0.076	0.035
0.00	0.18	0.647	-0.023	-0.006	0.071	0.052	0.032
0.00	0.21	0.470	-0.015	-0.035	0.096	0.083	0.031
0.00	0.24	0.576	-0.020	-0.020	0.086	0.071	0.033
0.05	0.24	0.593	-0.012	-0.016	0.078	0.067	0.037
0.05	0.20	0.620	-0.010	-0.013	0.078	0.067	0.035
0.06	0.17	0.638	-0.010	-0.002	0.077	0.066	0.035
0.06	0.14	0.426	-0.017	0.008	0.132	0.099	0.057
0.06	0.12	0.648	-0.014	0.003	0.086	0.072	0.037
0.06	0.10	0.626	-0.014	0.006	0.092	0.076	0.038
0.06	0.08	0.603	-0.012	0.009	0.102	0.080	0.041
0.07	0.06	0.585	-0.012	0.010	0.107	0.084	0.042
0.07	0.04	0.548	-0.011	0.010	0.114	0.090	0.046
0.10	0.23	0.584	-0.006	0.000	0.083	0.071	0.039
0.11	0.21	0.609	-0.003	0.004	0.081	0.068	0.038
0.11	0.18	0.613	-0.004	0.006	0.085	0.070	0.039
0.12	0.15	0.504	-0.011	0.010	0.121	0.093	0.046
0.12	0.13	0.595	-0.004	0.008	0.102	0.086	0.043
0.12	0.11	0.580	-0.007	0.010	0.107	0.086	0.044
0.13	0.09	0.546	-0.006	0.011	0.116	0.091	0.046
0.13	0.07	0.523	-0.004	0.011	0.118	0.092	0.048
0.15	0.24	0.573	-0.008	0.014	0.088	0.064	0.043
0.16	0.21	0.553	-0.005	0.013	0.091	0.065	0.044
0.17	0.18	0.521	-0.005	0.016	0.103	0.071	0.047
0.18	0.15	0.485	0.003	0.011	0.123	0.097	0.048
0.18	0.13	0.498	0.003	0.015	0.120	0.090	0.051
0.19	0.11	0.469	0.004	0.013	0.122	0.093	0.051
0.20	0.23	0.484	0.000	0.018	0.111	0.077	0.051
0.21	0.20	0.434	-0.004	0.016	0.121	0.085	0.055

Table I.9. Culvert Placed at an Embedment of 0.2D with a Discharge of 90 L/s

x (m)	y (m)	z (m)	$\bar{u}$ (m/s)	$\bar{v}$ (m/s)	$\bar{w}$ (m/s)	$RMS_{u'}$ (m/s)	$RMS_{v'}$ (m/s)	$RMS_{w'}$ (m/s)
0.5	-0.21	0.21	0.649	-0.006	-0.029	0.178	0.118	0.098
(Hole 2)	-0.20	0.23	0.731	-0.024	-0.035	0.148	0.101	0.084
	-0.18	0.14	0.478	-0.008	0.015	0.161	0.133	0.113
	-0.17	0.16	0.514	-0.011	0.005	0.168	0.129	0.115
	-0.17	0.19	0.633	-0.017	-0.013	0.178	0.118	0.104
	-0.16	0.21	0.736	-0.024	-0.024	0.140	0.099	0.085
	-0.15	0.24	0.804	-0.042	-0.030	0.099	0.079	0.064
	-0.13	0.08	0.597	-0.061	-0.009	0.159	0.145	0.086
	-0.13	0.10	0.602	-0.028	-0.002	0.153	0.123	0.093
	-0.12	0.12	0.608	-0.016	-0.002	0.153	0.126	0.097
	-0.12	0.14	0.639	-0.013	-0.004	0.162	0.123	0.094
	-0.12	0.16	0.676	-0.012	-0.004	0.159	0.117	0.087
	-0.11	0.18	0.753	-0.018	-0.011	0.136	0.103	0.070
	-0.11	0.21	0.821	-0.034	-0.013	0.091	0.082	0.054
	-0.10	0.23	0.840	-0.041	-0.018	0.075	0.071	0.046
	-0.07	0.05	0.709	-0.029	-0.003	0.108	0.086	0.058
	-0.06	0.07	0.745	-0.028	-0.002	0.099	0.084	0.058
	-0.06	0.09	0.770	-0.032	0.001	0.094	0.084	0.055
	-0.06	0.11	0.782	-0.030	0.007	0.102	0.088	0.055
	-0.06	0.13	0.805	-0.029	0.011	0.094	0.082	0.050
	-0.06	0.15	0.826	-0.029	0.013	0.087	0.077	0.048
	-0.06	0.18	0.833	-0.024	0.014	0.086	0.077	0.045
	-0.05	0.20	0.848	-0.027	0.004	0.075	0.069	0.041
	-0.05	0.22	0.853	-0.028	-0.003	0.069	0.068	0.041
	-0.05	0.24	0.849	-0.031	-0.016	0.067	0.067	0.038
	0.00	0.05	0.757	-0.049	0.018	0.082	0.080	0.047
	0.00	0.07	0.779	-0.039	0.029	0.076	0.076	0.049
	0.00	0.09	0.801	-0.028	0.033	0.075	0.074	0.047
	0.00	0.11	0.823	-0.025	0.031	0.073	0.070	0.045
	0.00	0.13	0.846	-0.020	0.028	0.068	0.066	0.040
	0.00	0.15	0.864	-0.017	0.026	0.062	0.063	0.039
	0.00	0.18	0.853	-0.015	0.019	0.069	0.069	0.040
	0.00	0.20	0.860	-0.013	0.006	0.064	0.066	0.039
	0.00	0.22	0.857	-0.017	-0.004	0.064	0.066	0.040
	0.00	0.24	0.851	-0.019	-0.016	0.065	0.067	0.039
	0.05	0.24	0.854	-0.010	-0.015	0.067	0.069	0.039
	0.05	0.22	0.858	-0.007	-0.006	0.067	0.067	0.041
	0.05	0.20	0.857	-0.001	0.000	0.067	0.070	0.040
	0.06	0.18	0.854	-0.003	0.005	0.071	0.071	0.040
	0.06	0.15	0.841	-0.003	0.005	0.077	0.071	0.042
	0.06	0.13	0.822	-0.008	0.002	0.085	0.076	0.046
	0.06	0.11	0.769	-0.029	0.008	0.110	0.092	0.059
	0.06	0.09	0.741	-0.051	0.003	0.115	0.097	0.064
	0.06	0.07	0.708	-0.068	-0.003	0.119	0.095	0.065
	0.07	0.05	0.688	-0.061	-0.006	0.116	0.091	0.062
	0.10	0.23	0.846	-0.007	-0.013	0.069	0.067	0.043
	0.11	0.21	0.848	-0.009	-0.017	0.073	0.072	0.044
	0.11	0.18	0.831	-0.011	-0.021	0.084	0.083	0.047
	0.12	0.16	0.796	-0.015	-0.029	0.109	0.095	0.060

	0.12	0.14	0.747	-0.028	-0.033	0.136	0.109	0.077
	0.12	0.12	0.683	-0.036	-0.028	0.153	0.115	0.095
	0.13	0.10	0.631	-0.041	-0.019	0.158	0.117	0.099
	0.13	0.08	0.577	-0.044	-0.002	0.169	0.134	0.096
	0.15	0.24	0.819	-0.005	-0.018	0.087	0.075	0.063
	0.16	0.21	0.773	-0.018	-0.019	0.122	0.091	0.076
	0.17	0.19	0.703	-0.024	-0.018	0.157	0.107	0.090
	0.17	0.16	0.589	-0.022	-0.014	0.175	0.128	0.109
	0.18	0.14	0.539	-0.020	-0.009	0.174	0.134	0.112
	0.19	0.12	0.632	-0.007	-0.001	0.187	0.141	0.111
	0.20	0.23	0.697	-0.024	-0.020	0.163	0.110	0.093
	0.21	0.21	0.622	-0.033	-0.016	0.181	0.122	0.103
1.5	-0.21	0.22	0.646	-0.030	-0.010	0.129	0.086	0.065
(Hole 5)	-0.20	0.24	0.689	-0.041	-0.008	0.119	0.078	0.061
	-0.19	0.12	0.498	-0.001	0.011	0.153	0.149	0.082
	-0.18	0.14	0.555	-0.020	0.006	0.135	0.100	0.069
	-0.17	0.16	0.606	-0.025	0.003	0.129	0.096	0.069
	-0.17	0.19	0.681	-0.036	-0.001	0.113	0.083	0.066
	-0.16	0.22	0.714	-0.040	-0.007	0.115	0.086	0.063
	-0.15	0.25	0.741	-0.041	-0.007	0.106	0.080	0.060
	-0.13	0.08	0.544	-0.027	0.007	0.133	0.098	0.061
	-0.13	0.10	0.592	-0.026	0.009	0.130	0.097	0.063
	-0.12	0.12	0.629	-0.024	0.009	0.125	0.094	0.064
	-0.12	0.14	0.650	-0.025	0.013	0.123	0.093	0.066
	-0.12	0.16	0.685	-0.030	0.009	0.118	0.091	0.062
	-0.11	0.18	0.727	-0.033	0.004	0.114	0.087	0.061
	-0.11	0.22	0.762	-0.035	-0.002	0.104	0.081	0.057
	-0.10	0.24	0.781	-0.038	-0.007	0.092	0.073	0.051
	-0.07	0.05	0.563	-0.027	0.014	0.128	0.093	0.057
	-0.06	0.07	0.618	-0.027	0.016	0.118	0.091	0.055
	-0.06	0.09	0.666	-0.025	0.016	0.113	0.088	0.056
	-0.06	0.11	0.701	-0.026	0.018	0.104	0.084	0.053
	-0.06	0.13	0.722	-0.024	0.021	0.105	0.083	0.053
	-0.06	0.15	0.745	-0.025	0.018	0.103	0.081	0.053
	-0.06	0.18	0.772	-0.025	0.013	0.098	0.076	0.052
	-0.05	0.20	0.792	-0.029	0.008	0.090	0.071	0.048
	-0.05	0.22	0.808	-0.028	0.004	0.085	0.067	0.045
	-0.05	0.24	0.816	-0.032	0.002	0.074	0.063	0.044
	0.00	0.03	0.513	-0.040	0.015	0.150	0.108	0.055
	0.00	0.05	0.588	-0.033	0.018	0.121	0.093	0.054
	0.00	0.07	0.637	-0.028	0.022	0.115	0.087	0.053
	0.00	0.09	0.675	-0.021	0.027	0.104	0.084	0.051
	0.00	0.11	0.719	-0.018	0.027	0.097	0.079	0.047
	0.00	0.13	0.752	-0.015	0.026	0.092	0.075	0.046
	0.00	0.15	0.779	-0.017	0.022	0.091	0.072	0.046
	0.00	0.18	0.803	-0.013	0.016	0.084	0.065	0.043
	0.00	0.20	0.827	-0.016	0.011	0.074	0.060	0.041
	0.00	0.22	0.831	-0.017	0.006	0.066	0.056	0.040
	0.00	0.25	0.827	-0.021	0.000	0.059	0.052	0.041
	0.05	0.24	0.833	-0.012	0.001	0.069	0.063	0.039
	0.05	0.22	0.835	-0.007	0.003	0.073	0.065	0.038
	0.05	0.20	0.828	-0.005	0.006	0.079	0.068	0.039

	0.06	0.18	0.810	-0.004	0.007	0.087	0.070	0.041
	0.06	0.15	0.792	-0.009	0.004	0.096	0.078	0.046
	0.06	0.13	0.766	-0.011	0.006	0.103	0.080	0.048
	0.06	0.11	0.731	-0.015	0.004	0.109	0.085	0.052
	0.06	0.09	0.692	-0.023	0.005	0.116	0.088	0.055
	0.06	0.07	0.646	-0.031	0.002	0.120	0.088	0.057
	0.07	0.05	0.600	-0.044	0.000	0.119	0.083	0.056
	0.10	0.24	0.817	-0.006	-0.005	0.081	0.070	0.043
	0.11	0.22	0.817	-0.006	-0.006	0.087	0.075	0.044
	0.11	0.18	0.785	-0.009	-0.005	0.101	0.080	0.051
	0.12	0.16	0.774	-0.011	-0.007	0.097	0.073	0.052
	0.12	0.14	0.742	-0.015	-0.008	0.109	0.078	0.055
	0.12	0.12	0.700	-0.022	-0.010	0.118	0.083	0.058
	0.13	0.10	0.640	-0.034	-0.006	0.132	0.091	0.062
	0.13	0.08	0.586	-0.044	-0.005	0.146	0.128	0.068
	0.15	0.25	0.777	-0.005	-0.002	0.088	0.065	0.053
	0.16	0.22	0.764	-0.009	-0.005	0.099	0.072	0.055
	0.17	0.19	0.725	-0.011	-0.005	0.111	0.081	0.061
	0.17	0.16	0.666	-0.019	-0.002	0.124	0.085	0.065
	0.18	0.14	0.612	-0.025	-0.003	0.130	0.090	0.066
	0.19	0.12	0.526	-0.045	0.001	0.168	0.131	0.070
	0.20	0.24	0.677	-0.006	0.007	0.128	0.080	0.065
	0.21	0.22	0.633	-0.011	0.005	0.136	0.092	0.068
4.0	-0.20	0.22	0.589	-0.029	-0.008	0.140	0.090	0.058
(Hole 8)	-0.19	0.25	0.643	-0.035	-0.004	0.130	0.084	0.057
	-0.19	0.12	0.441	-0.010	0.003	0.142	0.112	0.067
	-0.18	0.14	0.485	-0.018	0.007	0.142	0.085	0.059
	-0.17	0.16	0.541	-0.023	0.004	0.137	0.081	0.060
	-0.16	0.20	0.637	-0.032	0.000	0.135	0.086	0.058
	-0.16	0.23	0.680	-0.038	-0.001	0.125	0.080	0.055
	-0.15	0.26	0.713	-0.042	-0.006	0.107	0.075	0.051
	-0.13	0.08	0.455	-0.022	0.007	0.126	0.082	0.057
	-0.13	0.10	0.497	-0.017	0.007	0.136	0.096	0.060
	-0.12	0.12	0.531	-0.020	0.008	0.142	0.094	0.061
	-0.12	0.14	0.562	-0.022	0.009	0.136	0.092	0.061
	-0.12	0.16	0.613	-0.025	0.005	0.137	0.090	0.060
	-0.11	0.19	0.670	-0.029	0.004	0.129	0.090	0.057
	-0.10	0.22	0.721	-0.035	-0.001	0.116	0.084	0.053
	-0.10	0.26	0.748	-0.036	-0.006	0.102	0.079	0.050
	-0.07	0.05	0.494	-0.027	0.005	0.133	0.092	0.056
	-0.06	0.07	0.528	-0.024	0.007	0.128	0.090	0.058
	-0.06	0.09	0.564	-0.020	0.006	0.127	0.089	0.061
	-0.06	0.11	0.606	-0.020	0.007	0.121	0.085	0.059
	-0.06	0.13	0.639	-0.020	0.006	0.121	0.084	0.059
	-0.06	0.15	0.679	-0.024	0.004	0.113	0.080	0.057
	-0.06	0.18	0.717	-0.024	0.004	0.119	0.084	0.054
	-0.05	0.20	0.757	-0.028	-0.001	0.107	0.080	0.052
	-0.05	0.23	0.783	-0.031	-0.009	0.094	0.075	0.048
	-0.05	0.26	0.778	-0.033	-0.014	0.093	0.073	0.047
	0.00	0.03	0.512	-0.041	0.004	0.151	0.096	0.053
	0.00	0.05	0.549	-0.030	0.003	0.131	0.088	0.054
	0.00	0.07	0.602	-0.029	0.000	0.120	0.085	0.053

	0.00	0.09	0.630	-0.021	0.003	0.122	0.082	0.056
	0.00	0.11	0.663	-0.021	0.005	0.115	0.079	0.055
	0.00	0.13	0.688	-0.019	0.003	0.117	0.085	0.055
	0.00	0.15	0.718	-0.018	0.000	0.121	0.080	0.053
	0.00	0.18	0.754	-0.019	-0.001	0.114	0.077	0.050
	0.00	0.21	0.791	-0.020	-0.004	0.095	0.073	0.047
	0.00	0.23	0.803	-0.023	-0.009	0.085	0.067	0.044
	0.00	0.26	0.787	-0.023	-0.018	0.087	0.069	0.043
	0.05	0.26	0.782	-0.014	-0.014	0.092	0.075	0.044
	0.05	0.23	0.815	-0.014	-0.009	0.090	0.073	0.042
	0.05	0.20	0.810	-0.014	-0.003	0.093	0.076	0.043
	0.06	0.18	0.785	-0.013	-0.001	0.102	0.079	0.046
	0.06	0.15	0.780	-0.018	0.000	0.092	0.062	0.045
	0.06	0.13	0.743	-0.019	0.000	0.099	0.067	0.048
	0.06	0.11	0.710	-0.021	0.000	0.103	0.068	0.048
	0.06	0.09	0.672	-0.024	0.000	0.113	0.074	0.051
	0.06	0.07	0.624	-0.028	0.001	0.124	0.079	0.053
	0.07	0.05	0.571	-0.031	0.000	0.128	0.082	0.052
	0.10	0.26	0.796	-0.008	-0.002	0.095	0.077	0.044
	0.10	0.22	0.820	-0.007	0.002	0.091	0.073	0.042
	0.11	0.19	0.799	-0.014	0.003	0.093	0.068	0.043
	0.12	0.16	0.764	-0.018	0.002	0.105	0.072	0.046
	0.12	0.14	0.723	-0.020	0.002	0.111	0.077	0.048
	0.12	0.12	0.679	-0.020	0.000	0.125	0.082	0.052
	0.13	0.10	0.621	-0.025	0.000	0.130	0.086	0.054
	0.13	0.08	0.549	-0.031	0.002	0.141	0.101	0.058
	0.15	0.26	0.781	-0.006	0.014	0.101	0.073	0.047
	0.16	0.23	0.779	-0.007	0.009	0.104	0.077	0.048
	0.16	0.20	0.731	-0.008	0.009	0.121	0.083	0.053
	0.17	0.16	0.642	-0.012	0.009	0.134	0.087	0.059
	0.18	0.14	0.564	-0.017	0.009	0.141	0.093	0.063
	0.19	0.25	0.672	-0.003	0.015	0.132	0.086	0.060
	0.20	0.22	0.629	-0.006	0.013	0.139	0.091	0.061
6.5	-0.21	0.21	0.519	-0.027	0.003	0.138	0.086	0.060
(Hole 11)	-0.20	0.24	0.570	-0.029	0.005	0.127	0.081	0.058
	-0.19	0.10	0.280	-0.001	-0.003	0.173	0.099	0.068
	-0.19	0.26	0.609	-0.033	0.006	0.117	0.073	0.055
	-0.19	0.12	0.446	-0.026	0.010	0.142	0.104	0.063
	-0.18	0.14	0.502	-0.023	0.010	0.128	0.085	0.057
	-0.17	0.16	0.518	-0.024	0.012	0.142	0.094	0.060
	-0.16	0.20	0.595	-0.030	0.009	0.134	0.091	0.057
	-0.16	0.23	0.639	-0.033	0.006	0.128	0.086	0.054
	-0.15	0.27	0.671	-0.037	0.005	0.113	0.079	0.051
	-0.13	0.08	0.491	-0.035	0.006	0.132	0.100	0.055
	-0.13	0.10	0.527	-0.027	0.008	0.129	0.091	0.058
	-0.12	0.12	0.553	-0.025	0.010	0.129	0.087	0.057
	-0.12	0.14	0.572	-0.021	0.011	0.125	0.087	0.060
	-0.12	0.16	0.605	-0.025	0.010	0.120	0.082	0.059
	-0.11	0.19	0.641	-0.026	0.010	0.107	0.070	0.053
	-0.10	0.23	0.680	-0.030	0.004	0.115	0.081	0.053
	-0.10	0.26	0.697	-0.034	-0.002	0.103	0.080	0.049
	-0.07	0.05	0.545	-0.031	0.005	0.124	0.079	0.053

	-0.06	0.07	0.567	-0.024	0.008	0.129	0.089	0.056
	-0.06	0.09	0.599	-0.020	0.007	0.132	0.094	0.057
	-0.06	0.11	0.620	-0.022	0.008	0.124	0.090	0.058
	-0.06	0.13	0.653	-0.022	0.005	0.119	0.082	0.056
	-0.06	0.15	0.671	-0.023	0.004	0.111	0.079	0.055
	-0.06	0.18	0.692	-0.021	0.002	0.113	0.087	0.054
	-0.05	0.21	0.713	-0.025	0.001	0.105	0.078	0.051
	-0.05	0.24	0.725	-0.027	-0.007	0.094	0.074	0.048
	-0.05	0.27	0.713	-0.027	-0.012	0.089	0.070	0.046
	0.00	0.03	0.512	-0.022	0.005	0.138	0.104	0.052
	0.00	0.05	0.575	-0.023	0.005	0.129	0.086	0.052
	0.00	0.07	0.605	-0.023	0.006	0.125	0.083	0.055
	0.00	0.09	0.644	-0.023	0.004	0.115	0.075	0.053
	0.00	0.11	0.671	-0.020	0.004	0.105	0.070	0.053
	0.00	0.13	0.703	-0.021	0.002	0.102	0.071	0.051
	0.00	0.15	0.727	-0.023	-0.001	0.099	0.066	0.050
	0.00	0.18	0.734	-0.019	-0.004	0.093	0.072	0.047
	0.00	0.22	0.751	-0.020	-0.007	0.083	0.066	0.045
	0.00	0.25	0.745	-0.022	-0.015	0.077	0.063	0.043
	0.00	0.28	0.719	-0.021	-0.023	0.076	0.060	0.042
	0.05	0.27	0.739	-0.014	-0.012	0.096	0.081	0.043
	0.05	0.24	0.760	-0.015	-0.007	0.093	0.080	0.042
	0.05	0.21	0.773	-0.016	-0.002	0.095	0.080	0.043
	0.06	0.18	0.762	-0.019	0.001	0.100	0.081	0.045
	0.06	0.15	0.742	-0.020	0.003	0.106	0.081	0.047
	0.06	0.13	0.732	-0.019	0.002	0.106	0.077	0.047
	0.06	0.11	0.716	-0.021	0.002	0.103	0.070	0.047
	0.06	0.09	0.668	-0.021	0.004	0.117	0.078	0.051
	0.06	0.07	0.623	-0.021	0.005	0.124	0.083	0.053
	0.07	0.05	0.574	-0.017	0.005	0.131	0.090	0.053
	0.10	0.26	0.771	-0.010	0.003	0.079	0.061	0.040
	0.10	0.23	0.783	-0.012	0.007	0.084	0.067	0.042
	0.11	0.19	0.761	-0.017	0.008	0.099	0.074	0.046
	0.12	0.16	0.717	-0.016	0.008	0.115	0.082	0.050
	0.12	0.14	0.686	-0.015	0.007	0.119	0.084	0.053
	0.12	0.12	0.652	-0.012	0.006	0.126	0.089	0.054
	0.13	0.10	0.597	-0.013	0.008	0.136	0.096	0.057
	0.13	0.08	0.538	-0.008	0.010	0.142	0.103	0.057
	0.15	0.27	0.732	-0.005	0.017	0.112	0.082	0.050
	0.16	0.23	0.704	-0.007	0.017	0.123	0.086	0.055
	0.16	0.20	0.660	-0.009	0.017	0.134	0.092	0.058
	0.17	0.16	0.584	-0.005	0.014	0.139	0.099	0.065
	0.18	0.14	0.543	-0.004	0.014	0.143	0.097	0.063
	0.19	0.12	0.487	-0.001	0.011	0.164	0.128	0.071
	0.19	0.26	0.631	-0.003	0.017	0.130	0.086	0.061
	0.20	0.24	0.595	-0.002	0.018	0.127	0.076	0.059
	0.21	0.21	0.546	-0.006	0.019	0.134	0.085	0.064
7.5	-0.21	0.21	0.522	-0.027	0.008	0.127	0.074	0.056
(Hole 14)	-0.20	0.24	0.556	-0.027	0.008	0.124	0.074	0.057
	-0.19	0.26	0.571	-0.028	0.011	0.133	0.094	0.060
	-0.18	0.14	0.493	-0.022	0.014	0.130	0.090	0.059
	-0.17	0.16	0.542	-0.027	0.014	0.133	0.085	0.059

-0.16	0.20	0.602	-0.028	0.013	0.137	0.091	0.058
-0.16	0.23	0.638	-0.028	0.011	0.127	0.085	0.055
-0.15	0.27	0.673	-0.031	0.008	0.112	0.080	0.049
-0.13	0.08	0.514	-0.030	0.014	0.132	0.095	0.055
-0.13	0.10	0.551	-0.025	0.009	0.122	0.080	0.054
-0.12	0.12	0.584	-0.024	0.011	0.130	0.091	0.056
-0.12	0.14	0.605	-0.023	0.012	0.128	0.090	0.056
-0.12	0.16	0.618	-0.024	0.012	0.124	0.088	0.057
-0.11	0.19	0.654	-0.023	0.009	0.124	0.093	0.055
-0.10	0.23	0.679	-0.025	0.006	0.121	0.092	0.053
-0.10	0.26	0.692	-0.027	0.002	0.110	0.088	0.049
-0.07	0.05	0.557	-0.027	0.009	0.131	0.090	0.053
-0.06	0.07	0.598	-0.027	0.009	0.125	0.086	0.054
-0.06	0.09	0.638	-0.026	0.006	0.117	0.081	0.053
-0.06	0.11	0.649	-0.022	0.008	0.113	0.078	0.053
-0.06	0.13	0.671	-0.021	0.008	0.107	0.072	0.053
-0.06	0.15	0.694	-0.023	0.006	0.100	0.068	0.051
-0.06	0.18	0.705	-0.019	0.003	0.109	0.086	0.050
-0.05	0.21	0.725	-0.025	-0.001	0.102	0.083	0.047
-0.05	0.24	0.723	-0.025	-0.007	0.101	0.082	0.045
-0.05	0.27	0.707	-0.023	-0.014	0.098	0.081	0.045
0.00	0.03	0.552	-0.028	0.008	0.145	0.117	0.053
0.00	0.05	0.595	-0.022	0.009	0.136	0.098	0.052
0.00	0.07	0.647	-0.020	0.008	0.125	0.092	0.051
0.00	0.09	0.661	-0.022	0.006	0.122	0.086	0.050
0.00	0.11	0.696	-0.020	0.005	0.114	0.084	0.049
0.00	0.13	0.716	-0.021	0.005	0.110	0.082	0.048
0.00	0.15	0.736	-0.021	0.003	0.101	0.079	0.046
0.00	0.18	0.753	-0.020	-0.001	0.101	0.083	0.045
0.00	0.22	0.750	-0.019	-0.007	0.097	0.081	0.044
0.00	0.25	0.738	-0.019	-0.016	0.092	0.077	0.041
0.00	0.28	0.706	-0.018	-0.023	0.088	0.074	0.040
0.05	0.27	0.722	-0.011	-0.011	0.096	0.081	0.041
0.05	0.24	0.755	-0.011	-0.005	0.098	0.084	0.042
0.05	0.21	0.768	-0.012	0.000	0.097	0.084	0.042
0.06	0.18	0.769	-0.015	0.004	0.104	0.086	0.043
0.06	0.15	0.765	-0.018	0.005	0.100	0.079	0.044
0.06	0.13	0.737	-0.017	0.007	0.111	0.082	0.046
0.06	0.11	0.715	-0.016	0.009	0.116	0.087	0.049
0.06	0.09	0.686	-0.016	0.008	0.121	0.091	0.049
0.06	0.07	0.641	-0.016	0.010	0.117	0.080	0.050
0.07	0.05	0.581	-0.015	0.010	0.122	0.083	0.051
0.10	0.26	0.744	-0.007	0.008	0.103	0.087	0.044
0.10	0.23	0.761	-0.007	0.010	0.107	0.089	0.046
0.11	0.19	0.756	-0.008	0.011	0.112	0.091	0.046
0.12	0.16	0.718	-0.011	0.012	0.108	0.078	0.049
0.12	0.14	0.683	-0.011	0.013	0.106	0.071	0.050
0.12	0.12	0.655	-0.010	0.012	0.112	0.076	0.053
0.13	0.10	0.607	-0.006	0.015	0.123	0.083	0.055
0.13	0.08	0.561	-0.002	0.013	0.138	0.105	0.057
0.15	0.27	0.709	-0.004	0.020	0.116	0.088	0.052
0.16	0.23	0.687	-0.003	0.018	0.126	0.091	0.056

0.16	0.20	0.648	-0.003	0.021	0.136	0.096	0.060
0.17	0.16	0.586	-0.002	0.020	0.133	0.088	0.061
0.18	0.14	0.548	-0.004	0.017	0.139	0.091	0.061
0.19	0.26	0.621	-0.001	0.023	0.119	0.072	0.058
0.20	0.24	0.584	0.000	0.022	0.131	0.080	0.061
0.21	0.21	0.522	0.002	0.020	0.140	0.089	0.065